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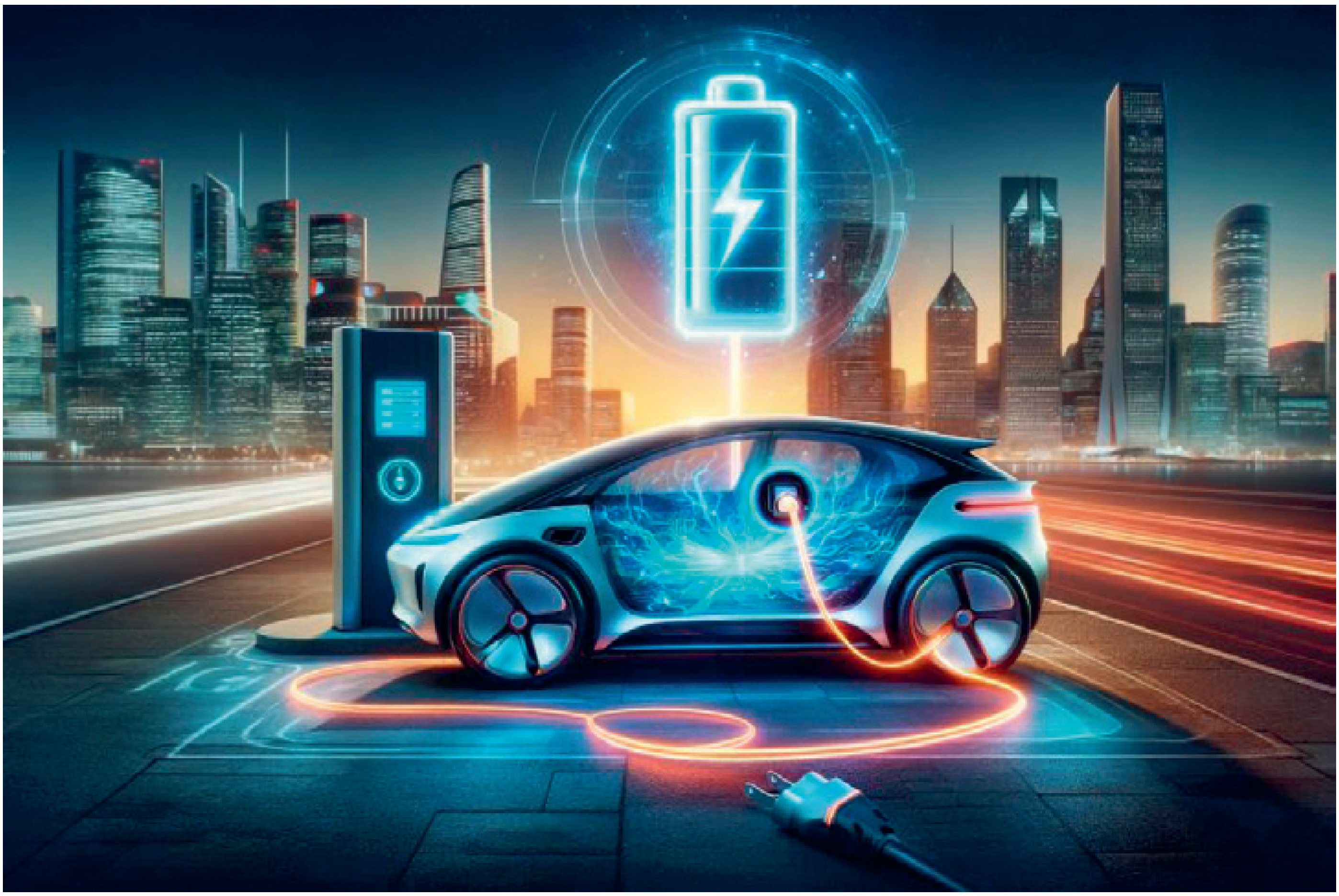

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- Provide international dissemination of knowledge and contributions to the science and practice in the field of traffic and transportation
- Promote and exchange information and knowledge in the transportation research arena and its application
- Explore the new trends in development and invention related to the efficiency, reliability, safety and economically and ecologically sustainable transportation.

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Editorial Office

Pan-European University Apeiron
Pere Krece 13, 78 000 Banja Luka, B&H
Tel: +387 51 247 910
Mob: +387 65 141 619
Fax: +387 51 247 921
http://www.tttp-au.com/
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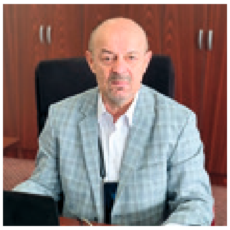

From the Editor

Dear readers,

It is my pleasure to present to you the 15th printed and electronic issue of the magazine " Traffic and transport theory and practice – TTTP" with its 10 authorised articles in the area of traffic and transport engineering. This time we are able to present different forms of solving traffic regulation issues at DLT junctions in Novi Sad. We also have an interesting analysis of traffic safety trends in Serbia for the period 2014-2024. Focusing of the contemporary technological solutions this time again the authors present possibility of using drones for real-time traffic data collection. We have presentation of RMSRM software solutions in defining optimal routes for transport of hazardous materials, as well as potential cyber-attacks and threats to autonomous vehicles in the VANET network. We did not forget about the battery safety in electric cars, passive road safety in terms of needs for protection of lateral interferences and decreasing consequences of traffic accidents.

Editor-in-Chief
Prof Danislav Draškovic, PhD Eng.

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ORIGINAL SCIENTIFIC PAPER

Analysis of the Possibilities for Improving Traffic Flow Conditions by Introducing a DLT Intersection in the City of Novi Sad

Aleksandar Milinković
Ph.D. Student, University of Novi Sad – Faculty of Technical Sciences, Novi Sad, a.milinkovic91@gmail.com

Vuk Bogdanović
Full Proffesor, Ph.D. in tehcnical sciences, University of Novi Sad – Faculty of Technical Sciences, Novi Sad, vuk@uns.ac.rs

Jelena Mitrović Simić
Associate Professor, Ph.D. in tehcnical sciences, University of Novi Sad – Faculty of Technical Sciences, Novi Sad, mjelena@uns.ac.rs

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Abstract: Displaced left-turn (DLT) intersections have gained their popularity because their implementation reduces control delay and improves the level of traffic safety. Their alternative configuration of traffic lanes enables the execution of left turns within the central part of the intersection without conflict with vehicles from the opposite direction. On the other hand, in Serbia, a large number of roundabouts have been constructed in recent decades for which no prior analyses of capacity and level of service were carried out, nor forecasts of traffic demand for the planned operational period. For that reason, some roundabouts exhibit very unfavorable traffic flow conditions with high vehicle delays, especially in situations when the circulating zone is blocked. Within this research, the possibility of applying a DLT intersection is considered by reconstructing a roundabout in the city of Novi Sad where unfavorable traffic flow conditions occur during peak hours. The analysis was conducted through a comparison of delays, queue lengths, and level of service in relation to a conventional (four-leg) signalized intersection as another proposed solution. The evaluation of traffic flow conditions was carried out through simulation in the Vissim software (Student version). By applying both proposed solutions, efficient traffic flow would be ensured, where the obtained parameters indicate the advantage of the DLT intersection.
Key words: DLT intersection, four-leg signalized intersection, control delay, level of service.

INTRODUCTION

One of the fundamental problems in the field of traffic regulation and management is the traffic flow conditions at intersections. When the traffic intensity exceeds the objective capacity of the intersection, control delays begin to increase sharply, and for that reason, the method of traffic regulation at intersections changes. One typical drawback of roundabouts is the inability to respond to high traffic demands due to blockage of the circulating zone, and thus of all approaches [1]. In that case, it is often a realistic possibility to carry out a reconstruction into a multi-lane signalized intersection. Also, under conditions of significant traffic loads, as a transitional solution between conventional and grade-separated intersections, Unconventional Alternative Intersection Designs (UAIDs) are increasingly applied in developed countries. These are signalized intersections where left turns are redirected, thereby reducing the number of conflict points in the central part of the intersection, and thus avoiding the addition of phases for protected left turns. The application of UAIDs shortens travel time [2] and improves the level of traffic safety [3-6]. Due to their more complex geometry, UAIDs occupy more space than typical intersections, so their application is often on the outskirts of cities where transit and local traffic meet.

The aim of this research is to examine the possibility of applying one of the UAID types in the city of Novi Sad at the location of a roundabout whose construction cannot efficiently ensure the flow of the existing traffic intensity. It concerns the *Displaced Left-turn* (DLT), also known as *Continuous Flow Intersection* (CFI) and *Cross-over Displaced Left-turn* (XDL). The analysis was conducted through a comparison of delays, queue lengths, and level of service in relation to a four-leg signalized intersection as another proposed solution. For the evaluation of parameters, the PTV Vissim software (Student version) was used [7].

At DLT intersections, left turns are redirected over lanes designated for opposing traffic before the central part of the intersection. The idea is that left turns are then served in the same phase together with through movements from the opposite direction, without conflict. As a consequence of this type of regulation, new, secondary intersections arise. A typical configuration of a full DLT consists of five intersections: one main and four newly created intersections at each approach (**FIGURE 1**). Traffic control at all five intersections is managed by traffic signals. It is common for right turns to be channelled and served behind the newly created intersections. In addition to full DLT, there are also partial DLT intersections (configuration with three intersections) where the displaced left turns are only located along the main corridor while the minor approaches have standard geometry. DLT and other UAID intersections have gained popularity through application in the United States of America. The state of Utah has more than ten DLT intersections, and they are also found in locations such as New York, Oakland, Louisiana, Los Angeles, Maryland, etc. [8], emphasising the success of this unconventional intersection design.

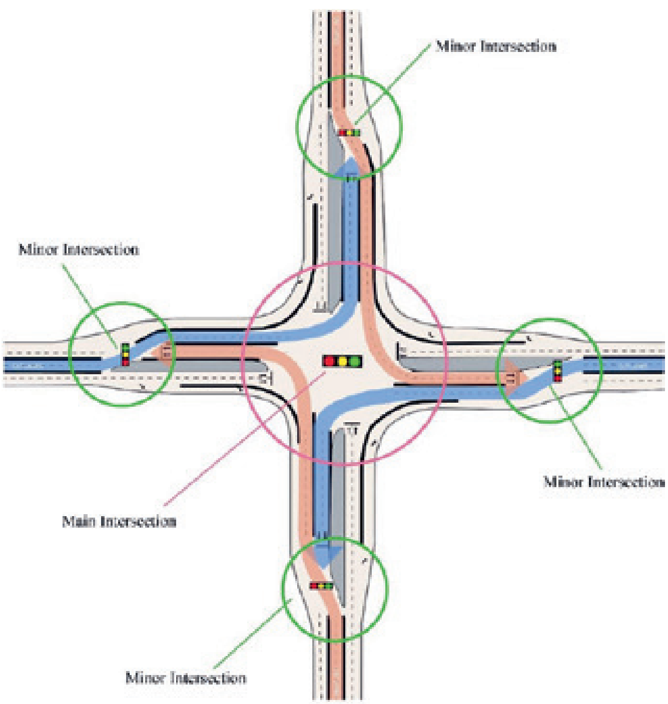

Figure 1. Typical concept of a full DLT intersection with left-turn paths. [9]

Performance of DLT Intersections

DLT intersections provide better operational performance than conventional signalized intersections in several aspects (delay, safety, environment), which is especially pronounced when the flow on the approaches exceeds 1000 veh/h [10]. In some cases, the capacity of a DLT intersection can be 80%, and even up to nearly 100% higher under saturated traffic flow conditions compared to conventional intersections [11-13]. Also, under unsaturated flow conditions, DLT intersections have better operational performance, where the number of stops is 15-30% lower compared to conventional intersections, and under saturated traffic conditions by 85-90% [14]. Furthermore, the performance of DLT intersections is also more favourable compared to roundabouts [15].

Also, DLT intersections are safer compared to standard signalized intersections [16]. The introduction of DLT can reduce the number of traffic accidents by 15-25% [3, 4]. However, a certain group of users requires time to adapt to driving through DLT intersections [17]. From an environmental and fuel consumption perspective, some studies [16, 18] give preference to DLT over conventional intersections, where, in cases of heavy traffic flows, emissions are reduced by approximately 10%

CURRENT STATE DESCRIPTION

The research area is the location of a roundabout in Novi Sad, formed by the intersection of Bulevar Evrope and Rumenački put (**FIGURE 2**). Bulevar Evrope represents one of the most significant roads in Novi Sad as it connects the urban areas of the city with the E-75 motorway, and at the same time is the longest boulevard in Novi Sad. The intersection is located in the wider central zone of the city. It consists of four legs with two traffic lanes each in the circulating area and entry arms. Due to high traffic flow demands, it is known that unfavourable traffic flow conditions occur at all approaches of the subject intersection, especially during peak hours, where traffic flows often become oversaturated – with delays exceeding 60, and sometimes even 100 seconds (level of service F).

Figure 2. Research area

The basis for the analysis was the real traffic load measured in the field during the peak hour. In the table (**TABLE 1**) the flows by direction are shown, after forming a conditionally homogeneous flow in passenger car units.

Table 1. Traffic Flow by Direction

Direction	1_2	1_3	1_4	2_3	2_4	2_1	3_4	3_1	3_2	4_1	4_2	4_3
veh/h	143	585	432	15	458	206	244	722	35	491	421	367
Approach total		1160			679			1001			1279	
Total						4119						

Due to the location of the intersection, pedestrian flows are negligible and were not taken into account. The research area is flat terrain, so a longitudinal slope grade of 0% was adopted.

METHODOLOGY

In the area of the Bulevar Evrope – Rumenački put, there is a possibility of reconstructing the roundabout into another form of multi-lane intersection. Two solutions with the same number of traffic lanes were proposed for evaluation:

1. Four-leg signalized intersection with four lanes on the approaches where right turns are channelled;
2. Full DLT intersection with four lanes on the approaches where left turns are displaced and right turns are channelled.

In recent years, two-lane roundabouts are often reconstructed into so-called turbo roundabouts, which are effective in situations where flows do not exceed about 3500 veh/hour [19]. This is one of the reasons why such types of intersections were not considered in the analysed case.

The geometries of the intersections for the proposed solutions were implemented in the PTV Vissim software (Student version) (**FIGURE 3**, **6**), where the evaluation of traffic signal operation parameters was also carried out. One of the limitations of the student version of this software relates to the simulation duration, which is limited to 600 seconds, and this was applied in the analysed case, with the evaluation starting from the 150th second (vehicle accumulation period – so-called "warm-up" of the simulation). The authors consider that in the analysed case this limitation on simulation length presents justified values of the measured indicators, because the evaluation for both proposed solutions resulted in delays reflecting conditions of unsaturated traffic flows, and vehicles rarely remain in the intersection area after the current cycle ends. Furthermore, to account for stochasticity, multiple simulations of 10 iterations each were conducted at the subject intersections (*Random Seed:* 12, 22, ..., 102), with the results analysed based on average parameter values.

To compare the efficiency of traffic operation under traffic signal control, it is necessary to optimise their functioning. In the case of fixed-time signal operation, this is achieved by calculating the elements of the signal plan, that is, determining the optimal cycle length and green times. To determine the optimal cycle length, data on the saturation flow rate are required, which for both proposed solutions was obtained using the HCM method [20].

Scenario 1 – Four-Leg Signalized Intersection

The proposed solution represents a signalized intersection (**FIGURE 3**) with four traffic lanes on the approaches (two through, one for left turn, and one channelized for right turn), of which the short lanes are those extending along the edges of the carriageway. The short lanes on the approaches were assigned lengths of 60 meters. The exits consist of three traffic lanes, with the short merge lane extending along the right edge of the carriageway. The width of all traffic lanes is 3.5 meters.

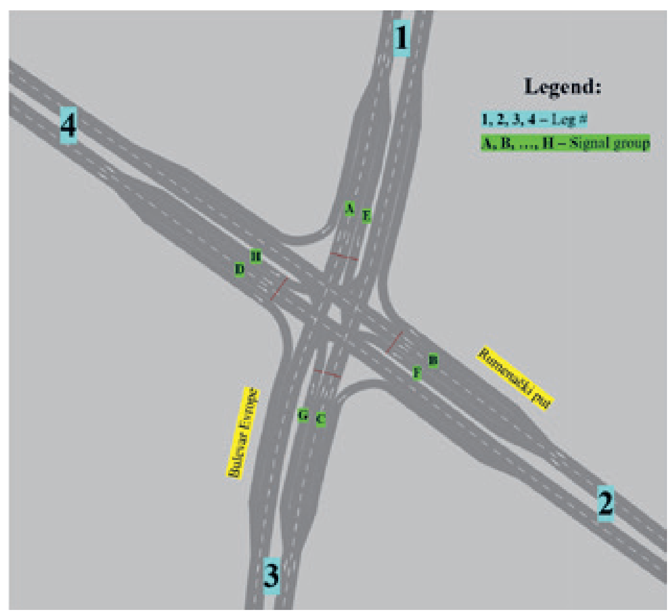

Figure 3. Layout for Scenario 1

Efficiency testing of the intersection was carried out using several different scenarios of signal plans and phase sequences. It was determined that the following phase sequence (**FIGURE 4**) provides a stable movement regime by directions and approaches, with the lowest values of control delay.

The calculation of the signal plan elements was carried out using the *Critical flow method* [21], where the optimal cycle length (C_o) is obtained as follows:

$$C_o = \frac{(1{,}4 + k) \cdot L + 6}{1 - Y} \quad (1)$$

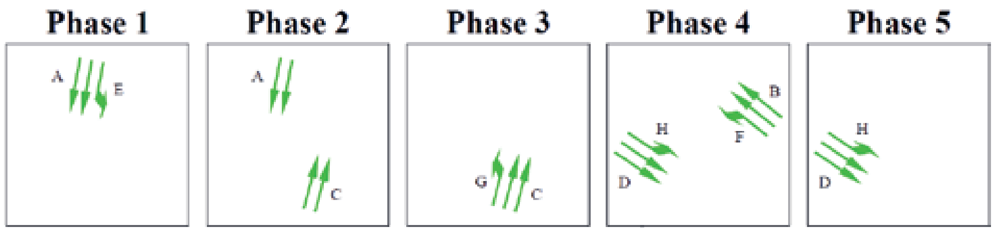

Figure 4. Proposed phasing diagram for Scenario 1

where:

- L – lost time during the cycle;
- Y – sum of the flow ratios of the signal groups forming the critical flow;
- k – additional optimisation parameter (for minimum control delay, the value k = 0 is adopted).

For the practical saturation degree values of all flows, the value $X_p = 0.85$ was selected. The lost time at start-up and the utilisation of the yellow interval were both adopted as equal, 2 seconds for all flows.

The adopted cycle length with the distribution of green times is presented using the standard display in Vissim (**FIGURE 5**)

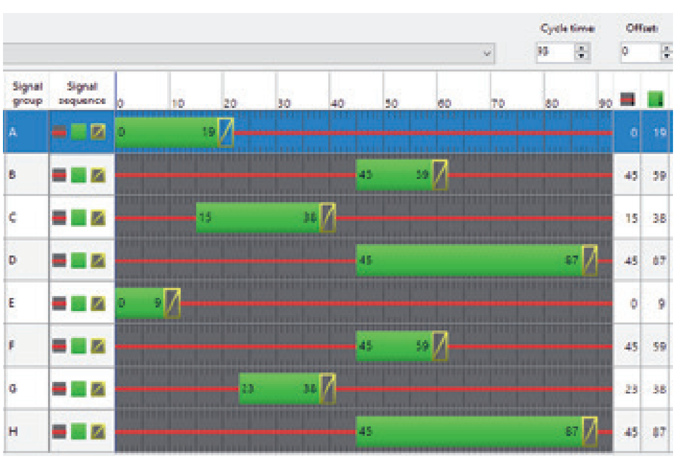

Figure 5. Signal settings for Scenario 1

Scenario 2 – DLT intersection

The proposed solution represents a full DLT intersection with displaced left turns on all approaches (**FIGURE 6**). All approaches to the central intersection zone (I1) consist of four traffic lanes (two through, one displaced for left turns, and one channelized for right turn), where the short lane is the one extending along the right edge of the carriageway with a length of 60 metres. Additionally, the displaced left-turn lane in DLT intersections is generally shorter than the lanes serving through movements, as it consists of two parts: a short lane before the displacement to the opposite side of the road (signal groups E′, F′, G′, H′) and a somewhat longer lane after the displacement (signal groups E, F, G, H). In the analysed case, the length of the northern approach is limited due to a bridge located approximately 130 metres from the centre of the intersection (**FIGURE 2**). For this reason, the length of the displaced left-turn lane is about 70 metres, which is slightly shorter than the standard length [8]. However, no issues were observed during the simulation, as the volume of vehicles turning left from that approach is not significant. Additionally, **FIGURE 6** shows that, due to limited space at certain roadside areas, the analysed DLT intersection has fewer lanes on the approaches compared to some standard solutions, which typically have two lanes for displaced left turns (**FIGURE 1**), and often even three lanes for through movements. All traffic lanes on the approaches and exits are 3.5 metres wide, except for the short left-turn lanes (signal groups E′, F′…), which are 3 metres wide.

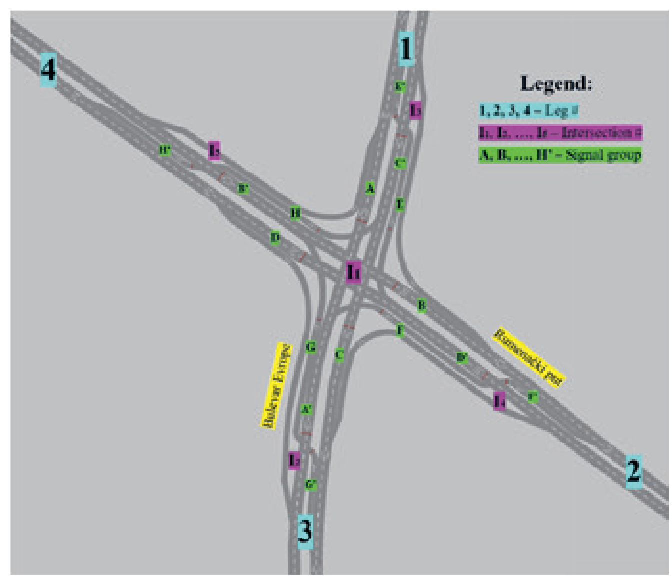

Figure 6. Layot for Scenario 2

The standard phase diagram for full DLT intersections consists of two main phases that cover all five intersections simultaneously (**FIGURE 7**). Traffic signal control can be implemented using a single controller that manages both the main intersection (I1) and the secondary intersections (I2, I3, I4, I5), or by using five separate controllers, one for each intersection, whose signal plans are coordinated through offset green times. In this case, the simulation of traffic flows in Vissim was conducted using a single signal controller.

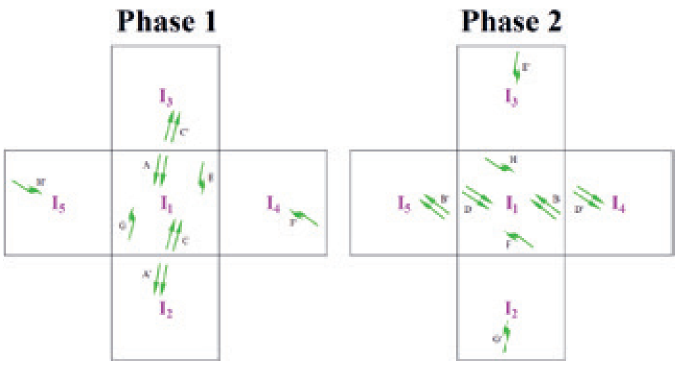

Figure 7. Basic phase diagram for a full DLT intersection

However, for even more efficient traffic flow, DLT intersections often implement a green time offset for the through movement signal groups (e.g. A→A′), which also creates an offset for the left-turn movements (e.g. E′→E). Achieving an ideal green time offset simultaneously for both through and left-turn movements would be quite complex, so a compromise should be made depending on the distribution of traffic loads. In the analysed case, an 8-second green time offset was applied, focused on through movements (**FIGURE 9**). As a result, the phase diagram becomes somewhat more complex, with the addition of two phases (interphases) (**FIGURE 8**).

In the case of applying either a single comprehensive or multiple separate signal controllers, it can be observed that control at all five intersections must operate with the same cycle length, and therefore [9]:

$$P_1 I_1 + P_2 I_1 = C \tag{2}$$

$$P_1 I_{2,3} + P_2 I_{2,3} = C \tag{3}$$

$$P_1 I_{4,5} + P_2 I_{4,5} = C \tag{4}$$

where:

- $P_1 I_1$; $P_2 I_1$ – first and second phase duration for intersection I_1;
- $P_1 I_{2,3}$; $P_2 I_{2,3}$ – first and second phase duration for intersections I_2 i I_3;
- $P_1 I_{4,5}$; $P_2 I_{4,5}$ – first and second phase duration for intersections I_4 i I_5.

$$C_o = \frac{1{,}5 \cdot L + 5}{1 - Y} \tag{5}$$

The calculation of the optimal cycle length and green times was carried out using the *Webster* method [22], based on the basic phase plan (**FIGURE 7**) relying on the signal groups within the main intersection (A-H). According to this method, the optimal cycle length is obtained as follows:

Based on the obtained cycle length and green times according to the basic phase plan, green time offsets are applied to the signal groups at the secondary intersections (**FIGURE 8**). Methodologies for calculating signal plans and traffic signal operation parameters for DLT and other types of alternative intersections can also be found in the HCM [23].

The adopted cycle length with the distribution of green times is presented in the signal settings (**FIGURE 9**).

Figure 9. Signal settings for Scenario 2

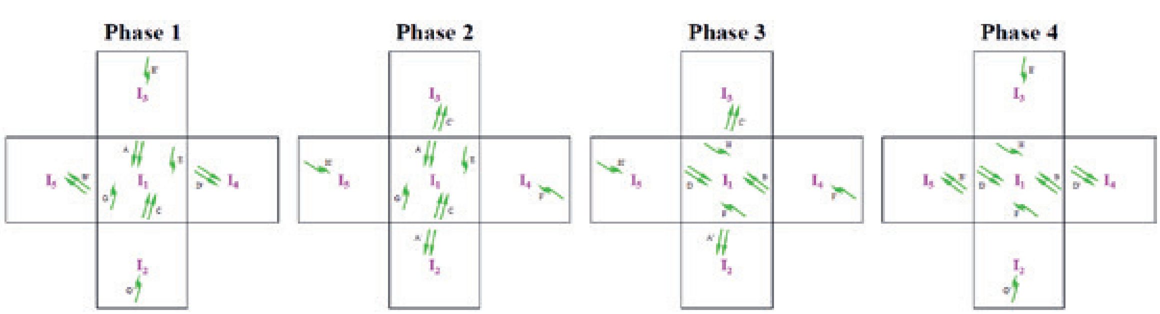

Figure 8. Phase diagram for Scenario 2 with green time offset

RESULTS AND DISCUSSION

Based on the evaluation in Vissim, a comparison of the proposed solutions was carried out (**TABLE 2**) according to the average vehicle control delay (**Delay** – s/veh), queue length (**QLen** – m), and level of service (**LOS**), for each direction and the entire intersection.

Table 2. Comparison of Output Results for the Proposed Solutions

	Four-leg signalized			DLT		
Direction	**Delay**	**QLen**	**LOS**	**Delay**	**QLen**	**LOS**
1_2	46,82	9,88	D	30,84	1,50	C
1_3	35,29	17,63	D	17,02	7,13	B
1_4	3,10	0,00	A	1,80	0,00	A
2_3	46,98	1,23	D	33,78	0,24	C
2_4	37,71	17,07	D	12,36	3.85	B
2_1	0,86	0,00	A	0,67	0,00	A
3_4	44,73	17,56	D	37,73	3,59	D
3_1	34,68	22,51	C	21,39	9,90	C
3_2	2,35	0,00	A	1,11	0,05	A
4_1	40,33	27,87	D	45,30	14,94	D
4_2	17,42	6,75	B	11,36	3,26	B
4_3	1,90	0,29	A	1,14	0,18	A
Average	**26,01**	**10,07**	**C**	**17,88**	**3,72**	**B**

As can be seen from **TABLE 2**, both proposed solutions would achieve efficient traffic flow (levels of service C and B). Although having fewer lanes than usual, the application of the proposed DLT intersection would reduce control delays by 31% compared to the subject four-leg signalized intersection. Thanks to the shorter cycle length and elimination of conflicts, delay for a single through movement (3_1) barely exceeds 20 seconds. All other delays above level of service B belong to left-turn movements. The reason is that vehicles arriving in the second half of the phase often have to stop up to three times to pass through the intersection (e.g. for movement 1_3, vehicles follow the signal path E′→E→D′). This often applies to a small number of vehicles (usually fewer than five), while other vehicles make use of the green wave between at least two signals in sequence, which can also be observed in the short queue lengths. Only for movement 4_1 are delays somewhat higher at the DLT compared to the four-leg intersection, because for a flow of 491 veh/h (**TABLE 1**), it would be desirable for the DLT to have two displaced left-turn lanes. However, although delays for movement 4_1 are somewhat higher at the DLT, the queue length for the same movement is almost half compared to the four-leg intersection, confirming the previous statement. A similar pattern in the Delay:QLen ratio between the analysed intersections is also observed for movement 3_4, as well as for certain through flows, thanks to the green time offset.

On the other hand, although the introduction of the DLT intersection would achieve better performance compared to the four-leg intersection, due to uneven traffic flows between certain approaches, the potential of this type of intersection is not fully realised. An example of this is movement 2_3, where during the peak period a traffic flow of only 15 veh/h was measured, yet the delays for this movement exceed 30 seconds for the aforementioned reason related to the path of the displaced left turns, as well as due to the load from the opposing movement 4_1, which causes a longer phase duration. At the four-leg intersection, delays for left turns at 2_3 are also increased because they are served simultaneously with movement 4_1, so that the busier flows in other phases can be served more efficiently

For the reasons mentioned, the cost-effectiveness of constructing and installing a DLT intersection can often be questioned. However, the application of a DLT intersection with a sufficient number of traffic lanes and a more favourable distribution of vehicle flows on the approaches could efficiently control circulation with traffic volumes twice as high as in the analysed case.

Figure 10. Simulation of vehicle movement for the proposed DLT intersection at the analysed location

CONCLUSION

This study analysed the possibility of applying a DLT intersection by reconstructing an existing roundabout where traffic flows often become oversaturated. In addition, the application of a standard multi-lane signalized intersection was considered. As parameters for evaluating the efficiency of traffic operation between the proposed solutions, control delay was primarily tested, followed by queue length and level of service.

It was established that the application of either proposed solution would achieve quite favourable traffic conditions, with a level of service B (DLT) and C (four-leg signalized), so from this aspect both scenarios could be considered functional solutions. The analysed DLT intersection would achieve a significant reduction in delays of around 31% compared to the four-leg. Nevertheless, in the analysed case, the potential of the DLT intersection was not fully realised. Besides the common spatial limitations for implementing DLT intersections with multiple displaced lanes, a large unevenness in vehicle flows on the approaches served in the same phase (especially left turns) limits its operational efficiency.

For the above reasons, before making a decision to construct such and similar types of alternative intersections, it would be advisable to thoroughly assess the cost-effectiveness of such a solution through functional evaluation, cost-benefit analysis, and, if possible, to consider the traffic load forecast with growth factors for a multi-year operational period. The described procedures could be classified as directions for further research.

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ORIGINAL SCIENTIFIC PAPER

Contemporary Procedures for Traffic Data Collection With a Special Emphasis on the use of Drones

Vladimir Ilić
Teaching Assistant, Master of Traffic Engineering, Faculty of Mechanical Engineering, University of Montenegro, Podgorica, Montenegro, vladimiri@ucg.ac.me

Valentina Mirović
Full Professor, Doctor of Science, Faculty of Technical Sciences, University of Novi Sad, Novi Sad, Serbia, plast@uns.ac.rs

Vuk Bogdanović
Full Professor, Doctor of Science, Faculty of Technical Sciences, University of Novi Sad, Novi Sad, Serbia, vuk@uns.ac.rs

Boško Matović
Assistant Professor, PhD, Faculty of Mechanical Engineering, University of Montenegro, Podgorica, Montenegro, boskom@ucg.ac.me

David Gruhonjić
Professional Associate, Master of Traffic Engineering, Faculty of Transport and Traffic Sciences, University of Zagreb, Zagreb, Croatia, dgruhonjic@fpz.unizg.hr

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Abstract: Traffic planning represents a key component of urban and regional development, requiring a comprehensive analysis of socio-demographic, spatial, and economic factors. The research is focused on the application of contemporary methods of traffic data collection, with particular emphasis on the use of drones in detecting the effects of specific traffic-calming measures. Specifically, two locations in Podgorica were analyzed, each featuring different types of speed-reduction devices: rubber elements and an asphalt platform. Aerial footage was captured using a "DJI Mini 3" drone, and the data were processed with the DataFromSky software. Statistical analysis was conducted using a t-test, which revealed statistically significant differences in vehicle speeds at the analyzed locations, with slightly lower speeds recorded at the site featuring rubber elements. The advantages of drones over fixed cameras lie in their flexibility, unobtrusiveness, and ability to capture real driving behavior, although there are temporal limitations on recording and challenges related to adverse weather conditions (rain and wind). The results indicate a high applicability of drones in the quantitative analysis of traffic flows, as well as the importance of appropriate method selection depending on the analytical objectives. The obtained data contribute to more accurate calibration of traffic models in software such as VISUM, AIMSUN, and PTV Vistro, thereby enhancing the quality of strategic planning decisions in urban traffic management.
Key words: traffic planning, drones, DataFromSky, traffic-calming measures, statistical analysis.

INTRODUCTION

Traffic planning is a complex scientific field that constitutes an integral part of development control, primarily within cities and subsequently within broader spatial units such as regions and states. This process is based on phenomena that are predictable and stable over longer periods of time (Vračarević&Basarić, 2014). As population mobility increases, the need to develop the transport system also grows, arising as a result of well-designed activities. The planning process begins with understanding the socio-demographic, spatial, and economic parameters within which the transport system operates. After that, it is necessary to identify the problems, challenges, and opportunities in the performance of the transport system in a given context, whether at the level of a state, province, region, or community. This typically involves conducting an analysis and evaluation of changes in the performance of the transport system, as well as examining the existing and anticipated challenges the system faces (Meyer, 2016).

Understanding the nature of the challenges a community faces represents an important starting point for the subsequent steps in the planning process. After that, the next phase involves developing a vision for the area covered by the study. Once the vision is established, it is further elaborated in detail so that the goals and tasks within traffic planning can later be clearly defined. The process of data collection and analysis, which is carried out after the goals and tasks have been determined, is based on understanding the current state of a transport system as well as the impact of certain changes planned for the future (Meyer, 2016).

An increase in the number of vehicles on the street network leads to numerous problems, such as insufficient parking capacity, the formation of traffic congestion that results in increased fuel consumption and heightened environmental pollution. In order to address these issues in the long term within the traffic planning process, it is essential to ensure reliable data collection as well as their adequate processing and interpretation. Today, various modern methods exist for traffic data collection, such as video and infrared cameras, radar devices, and similar technologies. One approach to collecting traffic data is the use of drones, which enable aerial recording of traffic flow. This paper presents precisely this methodology of data collection, where, for the purpose of researching the impact of two different traffic-calming elements on vehicle speed (deceleration) values in the traffic flow, an aerial recording was made using a "DJI Mini 3" drone. The research was conducted in the territory of the capital city of Montenegro, and the recorded video was processed using DataFromSky software. Specifically, the study observed rubber traffic-calming elements installed on Bulevar Crnogorskih Serdara and an asphalt platform located on Cetinjski put.

The results obtained through the research may be of considerable value for the implementation and planning of various traffic-calming measures in the future on the territory of Podgorica, as well as throughout Montenegro, in accordance with the effects achieved by installing the elements observed in the study.

METHODS OF DATA COLLECTION IN TRAFFIC

A large number of traffic data collection methods exist today, ranging from manual to fully automated procedures enabled by the development of modern technologies and devices. The advancement of intelligent transportation systems, which are increasingly discussed today, requires high-quality real-time traffic data. Various methods are used for traffic data collection. One of the most widespread is the use of inductive loops installed within the roadway, which record the passage of vehicle axles over them (Guillaume, 2008).

Several types of counters installed in the pavement can be distinguished, including pneumatic tubes, piezoelectric sensors, magnetic loops, and others. These counters are typically installed to obtain traffic flow data over a longer period on the observed road section. Additionally, traffic data collection can also be performed manually, as well as through the use of infrared cameras, handheld or stationary radar devices, and similar tools. Such methods are generally suitable for short-term data collection, making them useful for various research applications in the field of transportation.

Floating Car Data

This method of data collection is based on the principle of locating vehicles on the road network through mobile phones or GPS technology. The collected data related to the vehicle's location, speed, direction of movement, etc., are anonymously transmitted to a processing center. As for GPS technology, it was until recently available only in certain types of vehicles (such as taxi vehicles). The accuracy of this system is quite high (the error usually does not exceed 30 m).

Data collection using mobile phones refers to determining their position in space. This method of traffic data collection is advantageous because it does not require the acquisition of any additional devices or equipment. However, the system is characterized by lower accuracy in data collection (the error may reach up to 300 m) (Guillaume, 2008).

A Brief Overview of Previous Research

Numerous studies have used simple video techniques, in which the recorded footage was later analyzed manually in order to obtain the necessary data. The costs associated with this method of data collection are low compared to other methods, as it requires minimal human resources. However, manual processing of the recorded video is a time-consuming procedure. For this reason, various software packages have emerged to process recorded video footage, such as TRAIS, COUNTcam, Traffic Vision, TRAZER, MediaTD, Picomixer STA, etc. (Guillaume, 2008).

Real-world traffic conditions typically differ from homogeneous traffic conditions, in which speed is constant, driver behavior is uniform, and vehicle dimensions do not vary. Therefore, when collecting data for heterogeneous traffic flow, it is crucial to use appropriate methods that ensure sufficient accuracy of the obtained data. In field conditions, data commonly collected include vehicle speed, flow, density, direction of movement, distribution of traffic load at intersections by movement directions, and similar parameters (Jayaratne et al., 2020).

Within this study, the TRAZER software, the TIRTL (the infrared traffic logger) device, and the Google Distance Matrix API were tested for data collection in the territory of Sri Lanka. The research was conducted at a total of three locations. The data obtained using TRAZER and the API depend on the geometric parameters of the roadway, whereas the data obtained using the TIRTL technology do not. Therefore, the first two methods were applied at only one location. The analysis was carried out by comparing the data collected using the aforementioned methods with the data obtained through manual traffic counting (Jayaratne et al., 2020).

USE OF SURVEILLANCE CAMERAS AND UNMANNED AERIAL VEHICLES IN TRAFFIC

The installation of surveillance cameras at specific cross-sections of roadways has become increasingly common in recent times. There are many reasons for their growing use, primarily reflected in the detection of various traffic violations committed by drivers and in facilitating the clarification of traffic accidents. In addition, these cameras, when combined with different software tools, can also be used to collect various types of data relevant from the perspective of traffic planning, such as traffic flow, speed, traffic composition, and similar indicators (Slika 1). Their main advantage lies in the fact that they allow for 24-hour monitoring of traffic flows, 365 days a year, which provides continuity in collecting the desired data. On the other hand, the primary drawback of using surveillance cameras includes the relatively high costs of installation as well as the application of software required for automatic data processing. Accordingly, many locations are equipped with fixed cameras that record video footage 24 hours per day. In addition to their function in monitoring and detecting violations, surveillance cameras are increasingly used as intelligent sensors for estimating traffic density, thereby contributing to more efficient traffic management (Hu et al., 2023). Furthermore, research shows that speed enforcement cameras contribute to reducing vehicle speeds and the frequency of traffic accidents — a systematic review indicated that their application can reduce average speed by up to 15%, while the number of fatal and serious-injury crashes may decrease by as much as 44% (Wilson et al., 2010).

Figure 1. Fixed camera installed on a motorway section

Drones are unmanned aerial vehicles, meaning that no onboard pilot is required for their operation—control is instead carried out through a remote-control system. Andrijašević et al. (2024) used a drone for the purposes of a study conducted in Bar (Montenegro). Specifically, the impact of rumble strips on reducing vehicle speed in the area of pedestrian crossings was examined, and it was determined that a statistically significant difference exists between vehicle speeds before and after the strips, with the average post-strip speed being approximately 5 km/h lower.

The main advantage of this method of traffic data collection lies in the fact that a drone can be quickly and easily positioned at any location where specific data are required, which is not the case with fixed cameras. On the other hand, the greatest drawback of drones is the time-limited aerial recording, which depends on the capacity of the battery with which they are equipped. Modern lithium-ion batteries provide an autonomy of approximately 40 to 60 minutes, which is sufficient for most traffic research, but may present a challenge when long-term observation of traffic flow is necessary. In addition, this effective time must be further reduced by the period required for drone positioning — which typically does not take longer than 3 to 5 minutes after takeoff from the ground.

The sensitivity of drones to adverse weather conditions, such as windy or rainy weather, should also be emphasized—conditions that do not pose a significant problem for fixed cameras. Although more advanced and expensive drone models exist, offering moisture resistance and improved stabilization in windy conditions, the issue of strong wind gusts that may cause unintentional drone displacement during recording has not yet been fully resolved. For this reason, a very important technical component of modern drones is the gimbal—a three-axis camera stabilizer (roll, pitch, and yaw) that enables the camera to remain in a stable, fixed position regardless of the drone's movement. Thanks to this feature, it is possible to obtain clear and undistorted video footage even under mild turbulence, which is crucial when the recorded material is used for quantitative traffic flow analysis in specialized software.

One of the greatest advantages of drones in the field of traffic data collection lies in their small dimensions and low visibility — they are often not detectable to the naked eye from the driver's position. This means that drivers are usually unaware that they are being observed, which enables the collection of data on their real behavior, unlike fixed cameras whose locations are relatively quickly memorized by drivers, thereby influencing adjustments in their driving behavior. Consequently, the data obtained through aerial drone recording objectively reflect the actual state of the traffic flow at the location under investigation.

MATERIALS AND METHODS

As part of this research, an analysis was conducted to examine the influence of different traffic calming elements—raised asphalt platforms and rubber elements in the form of bumps on the roadway—at two locations in the capital of Montenegro, Podgorica, on vehicle speed and deceleration values within the traffic flow, as well as a mutual comparison of the obtained results. These types of measures are typically used for traffic calming in Montenegro. Both locations share similar geometric characteristics (physically separated carriageways with two traffic lanes each, approximately the same roadway width, no significant longitudinal gradient, etc.). The data were obtained using the DataFromSky software, in which the video footage previously recorded from the air by a drone, at a recording height of approximately 250 m above the roadway, was processed. Thanks to this method of data collection, real traffic-flow data were obtained, without any change in driver behavior resulting from awareness of being recorded. The main objective of the research is to determine the differences in vehicle speeds and decelerations at cross-sections placed at different distances from the traffic calming element (0, 10, and 20 m).

Data collection was carried out using a DJI Mini 3 drone, shown in Figure 2. This unmanned aerial vehicle weighs only 248 grams. It is equipped with a camera designed for photography at 12 MP with up to 60 fps, and for recording high-resolution 4K HDR video at up to 30 fps, with a field of view of up to 115 degrees. The drone can reach a speed of 5 m/s during ascent, while its maximum descent speed is 3.5 m/s. In horizontal flight, it can achieve speeds of up to 16 m/s. The gimbal ensures smooth and stable footage, even when flying in windy conditions.

Figure 2. Aircraft Used for Aerial Video Recording

DataFromSky

DataFromSky (DFS) is a software tool that offers various analytical solutions dedicated to traffic management (Figure 3). It provides high-quality processing of video recordings of traffic areas. The operation of the software is based on artificial intelligence. On the basis of the recorded video footage, it enables the determination of a wide range of traffic flow parameters that can later be highly useful in different types of analyses, such as: vehicle type and count in the traffic stream, speed, acceleration/deceleration values, following distance, time headway, time spent in a stationary position, trajectories, etc.

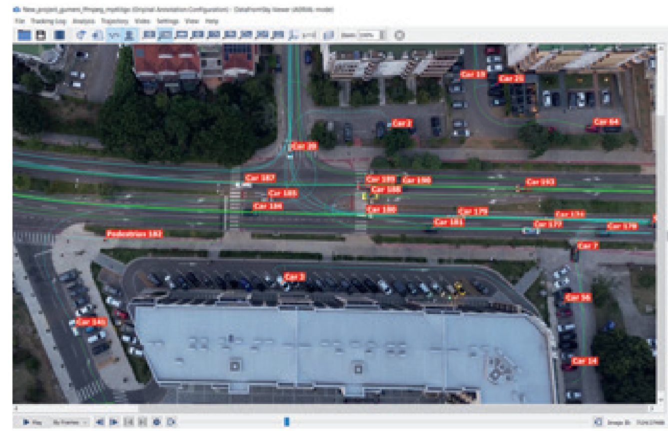

Figure 3. Interface of the DFS software

To record vehicle passage at a specific cross-section within the DFS software, we use so-called gates, which are defined as virtual points or sections placed at characteristic locations for the purpose of tracking the movement of objects such as pedestrians, cyclists, vehicles, and other traffic participants. Thus, gates can be placed not only at roadway cross-sections but also at the approaches/exits of an intersection, thereby enabling the determination of traffic load distribution by movement directions. In this way, traffic counting at intersections with high traffic volumes is significantly simplified, which—when performed manually—is especially challenging at roundabouts with a large central-island radius and a higher number of arms (Figure 4).

Figure 4. Gates Placed at a Roundabout

A very important parameter of the traffic flow is the vehicle speed. In order to obtain this value in the DFS software, expressed in km/h, it is necessary to perform so-called georeferencing, that is, to enter the coordinates of several points in space so that the software can recognize the mutual distances between them and thus determine the distance traveled per unit of time. Therefore, during field research, it is essential to determine the coordinates of at least four points in space. These should be characteristic points that can later be easily identified on the video recording (e.g., edge of the roadway, edge of the median island, traffic sign, street-lighting pole, etc.).

The coordinates are entered in the WGS 1984 coordinate system.

RESULTS

The research was conducted at two locations featuring different types of traffic-calming elements in Podgorica, on boulevard-type roadways. Figure 5 shows the location on Bulevar Crnogorskih Serdara, in the Gintaš–Union direction (hereinafter Location A), where rubber traffic-calming elements are installed, while Figure 6 shows the location on Cetinjski put, in the Budva–Center direction (hereinafter Location B), where an asphalt platform is placed. Both locations share similar geometric characteristics of the roadway. Within the DFS software, a total of six gates were defined (three for each direction) for each location. The gates marked as 0 m represent cross-sections placed exactly at the position of the traffic-calming element and act as exit gates for vehicles traveling in that lane. The gate positioned 20 m from the observed element serves as the entry gate, as vehicles encounter it first while moving along the roadway. Between these two cross-sections lies the 10 m gate, positioned exactly midway between the entry and exit gates.

Figure 5. Location A – Bulevar Crnogorskih Serdara

Figure 6. Location B – Cetinjski put

At both locations there are two traffic lanes for each direction of travel. Location A is an intersection where there was no substantial interference from vehicles on the minor approach, whereas at Location B there is a minor approach on the right-hand side for vehicles travelling from the City Centre direction. It may also be noted that here, too, there was no significant level of interference from vehicles on the minor approach, since on Cetinjski put the traffic lanes are physically separated, and it is therefore not possible from the minor approach to perform a left-turn manoeuvre towards the city centre. The speed limit indicated by traffic signs is 30 km/h at both locations. The height of the rubber traffic-calming elements is 5 cm, while the height of the asphalt platform is 4 cm, with an approach gradient of 1:10. As regards the asphalt platform, a pedestrian crossing is located on it, whereas the rubber elements are positioned immediately in front of the pedestrian crossings.

The statistical analysis of the data was conducted using the Statistica software. In order to ensure the relevance of the analytical results, vehicles whose minimum speed between the gates was below 4 km/h were excluded from the compiled database at the initial stage of data processing, as it is assumed that these vehicles were yielding to pedestrians crossing the roadway at marked pedestrian crossings, and therefore were moving at such low speeds.

The observed sample size at Location A, where rubber traffic-calming elements are installed, amounts to 407 vehicles, while at Location B, where the asphalt platform is located, it includes 293 vehicles. According to the data collected during the study, traffic frequency by direction at Location A was 194 vehicles (47.7%) in the Gintaš direction and 213 vehicles (52.3%) in the Union direction. At Location B, 154 vehicles (52.5%) were traveling from the Centar direction, while slightly fewer vehicles—139 (47.5%)—were traveling from the opposite direction (Budva). The average speed between the entry and exit gates at Location A was 21.51 km/h, while at Location B this value was 25.07 km/h, indicating a difference of 3.56 km/h. The average deceleration at Location B was –1.352 m/s^2, whereas at Location A it was –0.966 m/s^2, which means that vehicles experience greater deceleration at the location with the asphalt platform.

Speeds at the cross-sections

Speeds at the cross-sections vary depending on the distance between the individual cross-sections and the type of speed-calming device installed at the observed locations. Based on the data (Figures 7 and 8), the differences in speeds at the cross-sections can be observed in more detail by examining the Box & Whisker speed diagrams. The diagrams present the median values, the speeds corresponding to the 25%–75% range of the analyzed vehicle sample, as well as the minimum and maximum vehicle speeds recorded at each cross-section. The median represents a measure of central tendency in statistics—that is, the middle value of a dataset when the values are arranged in ascending order.

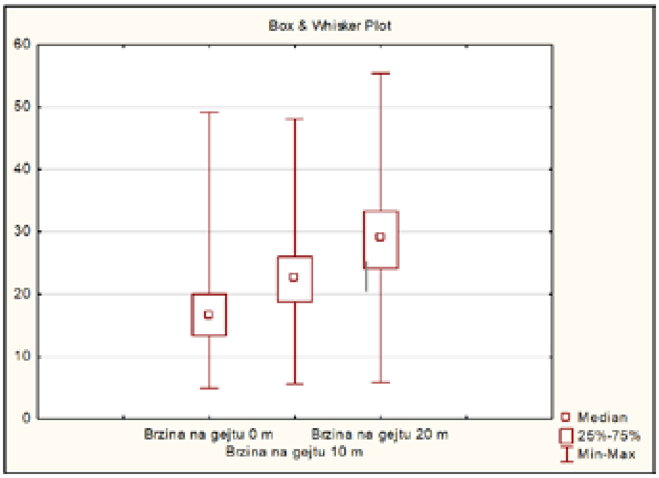

Figure 7. Box & Whisker Diagram for Speeds at Different Cross-Sections – Location A

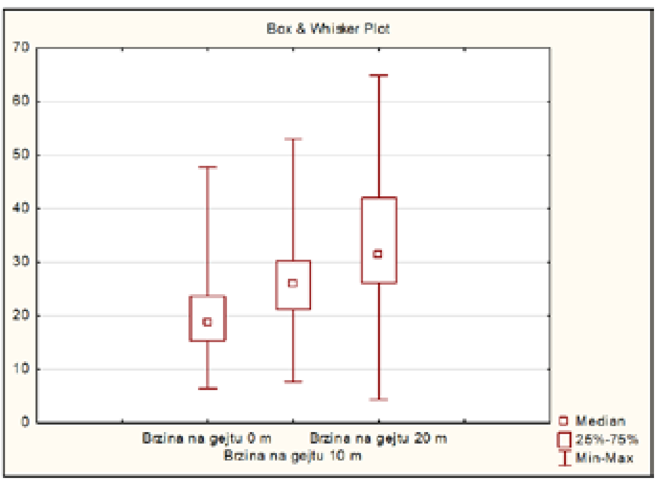

Figure 8. Box & Whisker diagrams for speeds at different cross-sections – Location B

The speeds of vehicles when passing over traffic-calming elements for 25% to 75% of the analyzed vehicle sample at Location A range between 13 km/h and 20 km/h, while at Location B the vehicle speeds are slightly higher, ranging from 16 km/h to 23 km/h. Observing the median value at the 0 m gate, we can note that the difference between the two locations is not large. The median at Location A is 17 km/h, whereas at Location B it is 19 km/h. Furthermore, it can be observed that at the 10 m gates there are differences between the speeds of vehicles representing 25% to 75% of the analyzed sample. At Location A, speeds range from 18 to 26 km/h, while at Location B they range from 22 to 31 km/h, indicating that vehicles were traveling at higher speeds at this cross-section (10 m gate – Location B). The median value at the 10 m gate is also higher at Location B, amounting to 27 km/h, while at Location A it is lower by 4 km/h. For the most distant cross-section — the 20 m gate — the median value is 32 km/h at Location B and 29 km/h at Location A. The speeds for 25% to 75% of the analyzed vehicle sample are higher at Location B, ranging from 27 km/h to 42 km/h, whereas at Location A speeds for the same percentile range from 24 km/h to 33 km/h. **Therefore, it can be concluded that the speeds at Location A (with rubber traffic-calming elements) are lower compared to Location B (with the asphalt platform).**

DISCUSSION

Based on the conducted research and the review of modern methods for traffic data collection, it can be concluded that certain methods offer different levels of suitability for specific planning objectives. Manual counts and drones are particularly useful for obtaining data on the distribution of traffic flows at intersections, with drones offering a significant advantage in terms of efficiency and the ability to cover complex intersections (Guillaume, 2008). For example, manual traffic counting is nearly impossible at large roundabouts that have two or more circulating lanes.

On the other hand, automatic traffic counters, such as inductive loops and radars, represent the most reliable solution for calibrating traffic models due to their ability to continuously collect large volumes of data (Guillaume, 2008). Software tools such as TRAZER and devices such as TIRTL provide additional information on traffic flow composition and speed, while the Google Distance Matrix API can be used to determine travel times and origin–destination matrices, with certain limitations regarding account availability and spatial coverage (Jayaratne et al.,2020).

Such data are essential for input and calibration of models in software packages such as VISUM, as well as other tools used for traffic network simulation and planning, including AIMSUN, TransCAD, and PTV Vistro (Shepelev et al.,2020). Their accuracy directly influences the quality of predictions that support strategic decision-making—from determining roadway capacities and traffic flow distribution to optimizing traffic signalization. Precisely calibrated models enable the identification of traffic bottlenecks, the prediction of the effects of new infrastructure solutions, and the testing of various scenarios without the need for costly and time-consuming field interventions.

Therefore, it can be concluded that the proper selection of data-collection methods—depending on the objective of the analysis (e.g., capacity assessment, traffic-flow distribution, travel-time estimation, or evaluation of infrastructural interventions)—can significantly enhance the accuracy, efficiency, and relevance of the planning process in urban environments. Combining traditional and modern methods, such as the use of automatic traffic counters, drones, and geolocation data, provides a multidimensional insight into complex traffic systems and facilitates data-driven decision-making.

CONCLUSION

Several modern procedures for traffic data collection have been presented in this paper. Special emphasis was placed on the use of drones, which make it possible to record aerial video footage and thereby collect the necessary data. Through subsequent analysis of the recorded footage in the DFS software, various traffic flow parameters can be obtained, such as traffic flow composition, distribution of traffic load at the intersection, vehicle speeds and acceleration/deceleration values at characteristic cross-sections, vehicle trajectories, and similar indicators.

On both locations observed in this study, the vertical traffic signage defines a speed limit of 30 km/h. At Location A, 45.2% of vehicles exceeded the speed limit, while at Location B the percentage of speeding vehicles was 55.6%. These values were obtained at the entry gate (gate 20 m). This indicates a higher share of speeding at the location with the asphalt platform. Based on the obtained results, it can be concluded that platforms significantly influence vehicle deceleration within the traffic flow. They affect not only the speeds during the passage over the speed-calming elements themselves, but also have a notable impact at 10 m and 20 m upstream of the element. The results of the analysis showed that, for the observed locations, rubber elements are more effective in reducing vehicle speeds compared to the asphalt platform, as speeds recorded at Location A were lower than those at Location B by approximately 3 km/h at gate 0 m. These results may be useful in planning future traffic-calming measures in urban areas of Montenegro, where excessive vehicle speeds represent a pronounced problem.

The study also highlights the significant potential of drones and specialized software solutions in the context of contemporary traffic planning. Their ability to provide high-quality aerial footage, together with their ease of use and minimal influence on driver behavior, makes them an exceptionally valuable tool for analyzing traffic flows, evaluating existing solutions, and subsequently calibrating transport models.

In conclusion, it can be stated that modern data collection methods—when carefully selected in accordance with the objectives of the analysis—represent a powerful tool in the hands of transport engineers and planners. By combining technology, statistical methods, and real-world field data, it becomes possible to make more reliable and efficient decisions that contribute to the long-term improvement of traffic safety and network performance. **This paper was carried out within the project "Development and Implementation of Sustainable Transport and Logistics Technologies in Teaching and Practice" (Department of Transport, Faculty of Technical Sciences, University of Novi Sad, 2025).**

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ORIGINAL SCIENTIFIC PAPER

RMSRM Software - Identification, Creation and Defining adr Routes and Dangerous Goods Transportation Management in Local Communities

Milorad Stefanovic
Master of Science in Traffic Engineering, CEO, Click & Find doo Beograd- Novi Beograd, Belgrade, Republic of Serbia, miccstc@gmail.com

Pavle Gladovic
PhD in Traffic Engineering, Engineering Academy of Serbian, Belgrade, Republic of Serbia, anaipavle@gmail.com

Radovan Viskovic
PhD Sc, Associate Professor, Doctor of Technical Sciences, University of East Sarajevo, Faculty of Technology, Zvornik, Republic of Srpska, Bosnia and Herzegovina, radovanviskovic1964@gmail.com

Zeljko Djuric
PhD Sc, Associate Professor, Doctor of Technical Sciences, University of East Sarajevo, Faculty of Transport and Traffic Engineering, Doboj, Republic of Srpska, Bosnia and Herzegovina, zeljko.djuric@fpm.ues.rs.ba

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Abstract: This paper introduces a remote system designed for comprehensive management of dangerous goods (especially oil and gas liquid fuels) shipments and haulage. The system integrates various functions to streamline the planning and scheduling of trips, duties, and task allocation for dangerous goods transport. It considers available resources, appropriate routes, suitable timeslots, and adequate infrastructure to ensure the safest and lowest-risk passage of dangerous goods shipments and haulages within the local community.

The paper details the system's concept, algorithms, functionalities, features, and architecture. It also outlines the system prototype and the experimental results prepared for a pilot program intended for a larger urban areas

Key words: risk management, planning, scheduling, allocation, monitoring, evaluation.

INTRODUCTION

Creating a safer and more secure environment necessitates the development of ongoing mechanisms that guide and positively influence the awareness and actions of individuals, companies (whose activity is the dangerous goods transportation), and institutions. This can be achieved by applying algorithms grounded in the principles, procedures, rules, and methodologies of developed appropriate risk assessment standards within a company's safety and resilience framework, with a specific focus on the impact and interaction related to the transportation of dangerous goods as outlined by ADR regulations [1] [2].

The increasing demand for the transportation of energy and hazardous materials, driven by the growth of mobility in modern society, unfortunately presents challenges to consistently ensuring compliance with regulations and rules for every trip and every entity. Despite the presence of numerous competent and inspection bodies, a significant portion of responsibility ultimately rests with individuals.

Day-to-day operations highlight the need for a tool that can significantly enhance the control, coordination, management, and forecasting of future requirements in the design and establishment of new ADR routes. This tool should be capable of distributing and collects data, information and results from its and others databases, providing synchronous alerts, and, when necessary, delivering files. System should also assist in identifying appropriate entities for business partnerships related to the transportation and distribution of dangerous goods. This includes all the stakeholders involved in designing, planning, supervision, legal compliance, education, and operations.

Table 1. provides an overview of the types of data collected from dangerous goods transportation vehicles, examples of specific data points, and the technologies employed for their collection.

Table 1. Vehicle Data Collection

Type	Data Example	Technologies
Vehicle status	Truck data: - Engine status - Fuel consumption - Brakes status - Tire pressure - Axles load - Speed *Semitrailer/Trailer data:* - Brakes status - Tire pressure - Axles load	Truck CAN bus[5] Additional sensors *Semitrailer/*Trailer CAN bus[6] Additional sensors
Driver status[7]	Driver data: - Driver Card Data - Driving and Rest Times - Driver Activity - Events and Error Messages Driver-related data: - Vehicle Speed - Distance Travelled - Country of operation - Vehicle identification	Tachogarph[8]
Cargo status[9]	- Towed Vehicle status and data - Temperature - Pressure - Open/Close valves - Open/Close doors - Quantities	Cargo sensors
Vehicle and Cargo documents[10]	- Transport documents - Driving license - Dangerous good transport card	Stored on the On-Board System

[5] Modern trucks commonly utilize standard fieldbus network technologies, such as the CAN bus, for managing vehicle diagnostic data. The Controller Area Network (CAN) system facilitates communication between various electrical components within the vehicle using a single or dual-wire setup. For further information on the specifics of the available data, please refer to [3].

[6] Semitrailer/Trailer electronics is evolving to the use of standard fieldbus technologies with the aim of integrating all on board electronic equipment. VISIONS project invested on trailer electronic data management as the semitrailer/trailer is responsible for most of the vehicle weight and is at the origin of most accidents. For further information on the specifics of the available data, please refer to [4].

[7] By EU regulations it is mandatory to install a tachograph in new vehicles having a mass of more than 3,5 tones when they are intended for the transport of goods... For further information on the specifics of the available data, please refer to [5].

[8] The tachograph is the device that records driving time, breaks and rest periods as well as periods of other work and availability of drivers engaged in the carriage of goods or passengers by road. The purpose of the tachograph is to enable controls of compliance with the set of EU rules aimed to prevent driver fatigue and to contribute to good working conditions of drivers, road safety and fair competition. For further information on the specifics of the available data, please refer to [5].

[9] VISIONS project invested specially on dangerous goods data collection, as the monitoring of such goods strongly impacts on safety.

[10] This type of data includes all information typically contained in law-enforced documents generally available in paper form. The electronic management of such documents makes inspection more efficient.

RESULTS

The Risk Management System for Routing and Monitoring (RMSRM) main function are:

- Collecting vehicle and driver, in an on-board information hub and infrastructure data in an information hub.
- Make data available to external information systems as interactive services.

Table 2. Vehicle Data Delivering

Task	Function	Adopted Technologies
Management of wireless communications	- Wireless networking in local area and wide area - Log on / Log off detection - Dynamic allocation of IP/ Hostname to hosts - Names resolution	WI-FI[11] GPRS[12] *Logoff Service[13]* DHCP [6] DNS
Support of a domain-specific open interface between ground applications and on-board applications	- Messaging - Service Interface Definition (SID) - Security - Map editing	XML [7] SOAP [8] WSDL [9] WSS [10] G3 [11] QGIS [12]
Management of temporary available network services	- High dynamics service discovery - Location awareness	UDDI [13] *Trigger Engine[14]* *Location Registry[15]*

[11] In the proximity of a local road infrastructure, information passes through a wireless LAN connection. WI-FI network support higher data rates than the GPRS network and for this reason it is used in the proximity of VISIONS enable infrastructures, where a high amount of information must be transferred, for example performing a large amount of cargo data.

[12] When the vehicle needs to transmit or receive data to or from a remote system, the mobile GPRS network is used. The GPRS network is characterized by a lower data rate, but its coverage is potentially unlimited, see [4].

[13, 14,15] See chapter 2, 2.1 and 2.2 and 2.3.

For the RMSRM system is selected a Service-Oriented Architecture (SOA) due to its inherent interoperability. This allows us to effectively integrate and work with diverse applications across different organizations, which is particularly beneficial for the complex software systems often found in large enterprises.

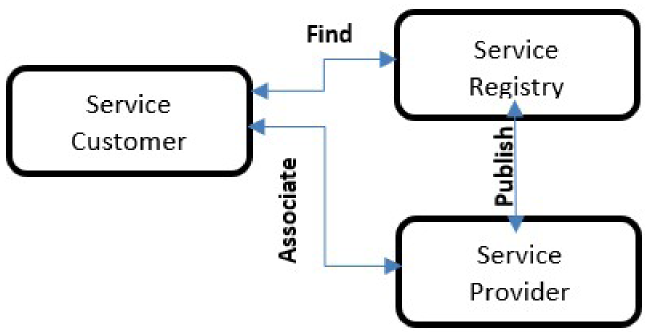

Figure 1. Presents basic interaction of Service Oriented Architecture. SOA defines three main actors: the Service Consumer, the Service Provider and the Service Registry. Providers publish the services they offer to a Service Registry. Consumers interrogate the Registry to discover the services they need and to obtain all the information needed to access such services.

SOA approach will leverage web services that adhere to standard internet protocols. These web services will primarily be implemented using:

- SOAP for messaging.
- WSDL for service interface description.
- UDDI as a service registry.

In this setup, the UDDI will serve as a directory, storing the addresses of service providers for specific services and links to their respective Service Interface Definitions (SID). The Information System architecture is created from the following modules:

Mobile Services

The Risk Management System for Routing and Monitoring (RMSRM) architecture builds upon the advancements of existing systems like VISIONS. These systems have successfully adapted Web Services technologies for wireless mobile environments, partly using Free and Open-Source Software (FOSS) and available software in the possession of regulatory bodies and countries. This approach facilitates access to crucial information and databases necessary for effective real-time risk management. The following paragraphs describe the architectural components added for this purpose.

Location Registry Module

Currently, the SOA Service Registry does not include support for location services, which are crucial for tracking the whereabouts of vehicles. To address this, RMSRM Location Registry stores location information as an additional attribute for the services already within the Service Registry. This enhancement allows applications to query the system more effectively by filtering requests based on specific location criteria.

Consequently, the Location Registry enables various users and applications to access different services based on service location and specific conditions. For instance, a consigner's administration or an ADR Competent authority or vehicle inspection body might only need to track trucks approaching or leaving a loading point or an authorized technical inspection station, particularly if the vehicle has a prior modification or remanufacturing or reconditioning record [14] [15] [16]. In contrast, the police might be interested in monitoring all vehicles within a defined geographical area, such as an ADR parking zone.

RMSRM architecture is designed to process four types of location information: geographic coordinates, rules, constraints, and points of interest. A point of interest refers to a specific location within the infrastructure, such as a road, intersection, gate, or parking space. The system can associate both a set of geographic coordinates and a relevant point of interest, along with any applicable rules and restrictions for them.

Trigger Engine Module

Trigger Engine component provides a valuable signalling mechanism to applications whenever a specific change occurs within the Service Registry or the Location Registry. Trigger Engine functionality allows applications to stay informed about relevant events without the need for constant polling of the registries.

For example, triggers can be activated by events such as:

- A vehicle joining the Service Registry.
- A vehicle leaving the Service Registry.
- A vehicle arriving at a specific point of interest.
- A vehicle departing from a specific point of interest.
- A newly registered vehicle offering a particular service.
- A vehicle entering a designated geographic area.
- A driver joining the Service Registry.
- A driver obtains new attribute (e.g., extension of possessed license, police notice)

Consequently, the Trigger Engine ensures that applications have up-to-date information regarding the available services at any given time. This is particularly beneficial in dynamic environments with frequent changes, such as mobile networks where vehicles routinely connect to and disconnect from the infrastructure, leading to rapid shifts in service availability.

Logoff Service Module

Functionality of the Logoff Service, which plays a crucial role in managing vehicle service registrations within an infrastructure. When a vehicle connects, it must register its availability at Service Registry. However, disconnections are often abrupt due to the nature of wireless coverage.

The Logoff Service Module addresses this by continuously monitoring the network to detect when a vehicle leaves the infrastructure's coverage area. Upon detection, it automatically removes the vehicle's entry from the Service Registry. This process necessitates interaction between the Logoff Service and the network infrastructure to ensure accurate and timely deregistration.

Trip Tracking Module

The Trip Tracking Module is designed to comprehensively monitor compliance with legal requirements, established rules, criteria, and performance indicators across all facets of individual driver work tasks. It offers real-time comparison of efficiency, quality, and quantity of individual task performance against existing database information based on predefined rules and objectives. The data is then recorded in the appropriate RMSRM registers.

Tachograph Module

The Tachograph is an approved, user-friendly measuring device installed in every vehicle for dangerous goods transportation. It is designed for the secure collection, processing, storage, and transmission of accurate and reliable data related to the driver, driver activity, and the vehicle itself. The Tachograph Module acts as middleware, enabling RMSRM to collects several key pieces of data relating to vehicle and driver activity, stored both in the Tachograph 's mass memory and on the driver's card, monitor driver behaviour by continuously sending queries and collecting data.

This allows for the identification of drivers and their behaviour during work tasks, particularly along predefined itineraries, and points of interest. It also provides real-time information and time intervals of events, ensuring adherence to prescribed rules and procedures.

Vehicle Module

The Vehicle Module focuses on collecting relevant and robust data from all available vehicle sources. These sources include the CAN (Figure 2.), tachograph, and other integrated vehicle sensors and devices, such as the onboard vehicle's computer, camera, driver fatigue detection system, and following vehicle distance detection system. This data is crucial for determining the vehicle's status and condition [17].

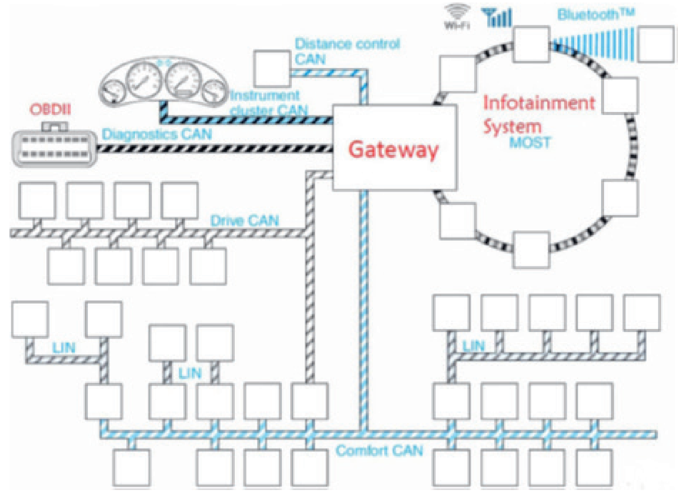

Figure 2. Presents Area Network (CAN). CAN is the most established automotive communication system protocol for the internal vehicle network. It allows safety-critical ECUs that attached to it to sufficiently broadcast information in the form of CAN packets between them and other connected busses (e.g., FlexRay, MOST, LIN) through several gateways [18]

The data collected from the vehicle, along with information from GPS devices and other available devices like upgraded video surveillance systems and alco-testers, are processed, stored, and distributed within the RMSRM database.

Inspection Authorities Module

The core function of inspection authorities is to act preventatively. This is achieved by monitoring the implementation of legislation and regulations through document control, field inspections, and supervision during incidents, with conclusions drawn from factual findings.

The Inspection Authorities Module aims to significantly enhance these processes and procedures, both quantitatively and qualitatively, by streamlining operations and substantially increasing the sample size of inspections, whether automatic or ad hoc.

The collected data, information, and documents would then be processed by the RMSRM. Based on predefined criteria, rules, and forms, it would synthesize the results of multi-criteria monitoring into comprehensive reports and interactive reviews.

These reports are categorized by monitored entities (such as companies, organizational units, managers, individuals, fleets, and vehicles) and controlled elements (including adherence to prescribed periods and scope of vehicle and driver controls, use of ADR parking lots and ADR transportation predefined routes, and details of transported documents, goods, and transported quantities).

Figure 3 and Figure 4 demonstrates a sample report, and the user interface clearly displays the selected perpetrator's behavior rating, including a list of violations, their locations, and times of occurrence.

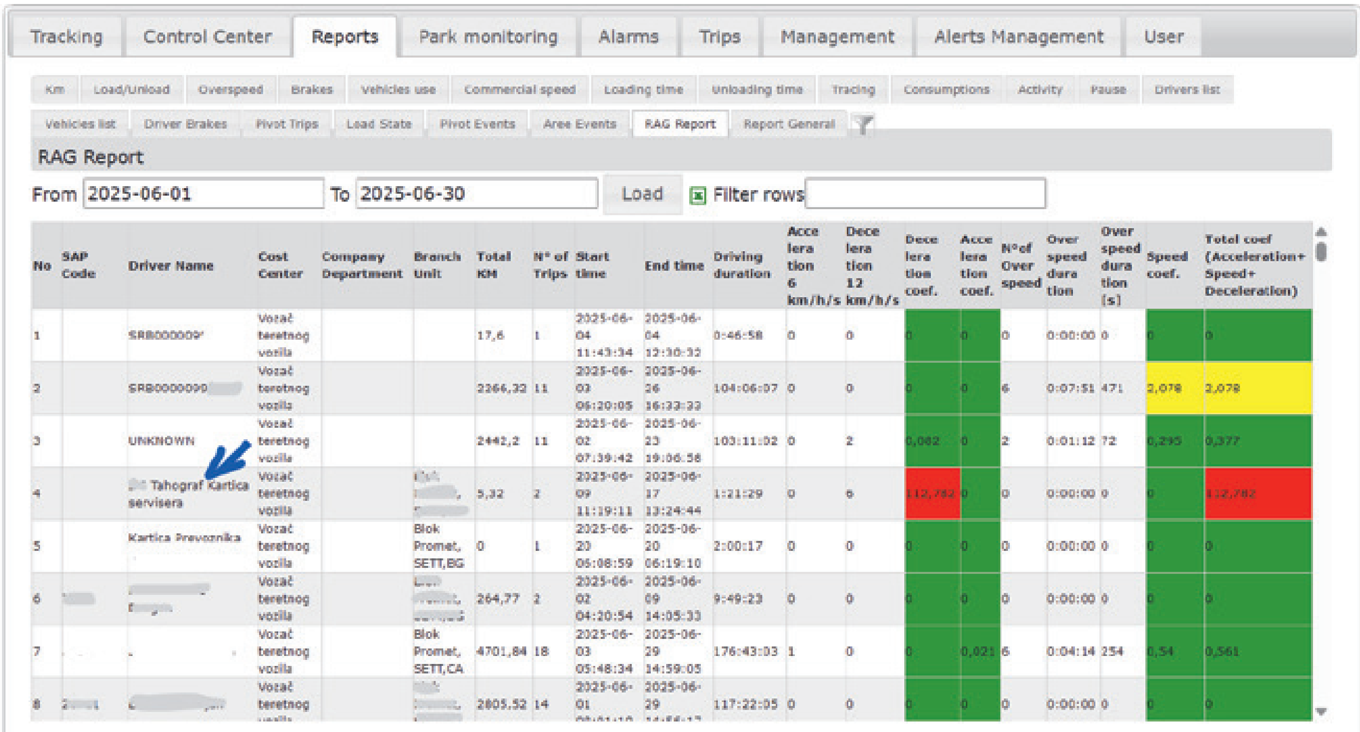

Figure 3. Presents RAG (Red, Amber, Green) Report

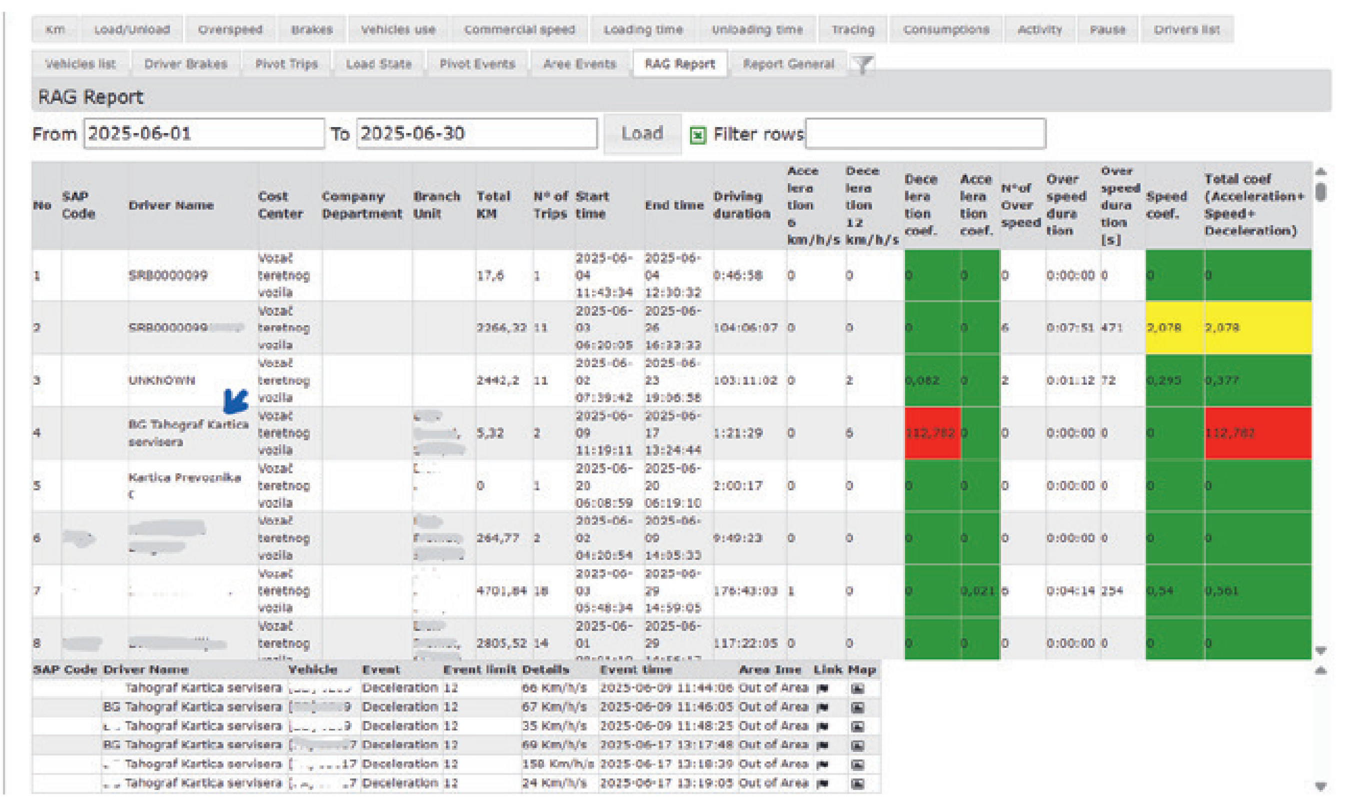

Figure 4. Presents result of the digging-in detected red fielded entity in RAG (Red, Amber, Green) Report and its content (violated rule/ restriction, locations of the violations, violation durations, vehicle's fleet number and driver's ID)

Inspection Authorities Module

The Supervisory Authority Module is designed to centralize and manage publicly available data from diverse institutions, including the police[1], courts[2], and medical facilities over standard application programming interfaces (APIs). This consolidation encompasses critical information such as driving license validity[5], violation records[3], driver and vehicle details, fine payments[6], initiated legal proceedings, judgments, and psychophysical assessments for various license holders. Additionally, the module integrates data from ministries and bodies overseeing transportation, economy, energy, infrastructure4, and construction[5].

Currently, accessing this information is challenging, often involving lengthy bureaucratic requests or fragmented searches across multiple websites. This difficulty in data exchange impedes coordination among relevant parties within economic and state entities. The RMSRM system's architecture addresses this by enabling seamless digital service exchange and direct transmission of crucial data among various bodies, institutions, companies, organizational units, and responsible personnel.

This system significantly enhances the efficiency and reliability of rule implementation, promoting transparency and effectively minimizing the risk of unauthorized or sanctioned entities participating in any process.

DISCUSSION

A key aspect of this system is its multi-layered, real-time monitoring capabilities. It delivers timely alerts and reports to all pertinent stakeholders regarding events, regulatory compliance, and the adherence to rules by everyone involved in the complete dangerous goods transportation process. The system facilitates the exchange, requests, collection and processing of data in real time between all parties directly and indirectly involved in the transportation of dangerous goods. This is done efficiently, within established deadlines and according to pre-defined rules, using comprehensive RMSRM databases.

The system's architecture allows for smooth and seemless digital service exchange between vehicles and road infrastructure components, such as roads, key traffic intersections, schools, hospitals, authorities data bases, tunnels, highways, O&G operators depots and its monitoring system (bottlenecking, throughputs, accumulations and expected state at the expected time of arrival) etc [19] [20]. This enables the direct transmission of important data from vehicles (including informations related to driver, engine status, cargo specifics, vehicle cargo space status, and cargo documentation, and all this in relation to the regulations) to the various information systems mentioned above (e.g. information systems of infrastructure, supervisory, emergency, supervisory authorities, etc.).

In the RMSRM is implemented a easy customizable subsystem where events and behaviors categorized as high importance or high risk automatically trigger notifications and alarms on designated equipment. This ensures timely action by the institution and/or end-user. In addition, all data is securely stored in the system databases and is accessible through user-friendly reports.

CONCLUSION

The paper provides a detailed description of the system's concept, algorithms, functionalities, features, and architecture. It also covers the system prototype and experimental results, which were prepared for a pilot program targeting larger local communities.

Built with a service-oriented architecture, the system incorporates specialized extensions designed to address the unique requirements of the field, such as managing highly dynamic events and adapting to short service lifetimes within the network.

The application of this system is expected to improve traffic safety in urban areas by reducing the risks of potential accident situations.

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[2] Register of unpaid fines and other monetary amounts in Serbia. Link: https://rnk.sipres.sud.rs/

[3] Notifications on traffic violations per driving license number in Croatia. Link: https://eprekrsaji.mup.hr

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https://mgsi.gov.rs/lat/prevoz-putnika-i-tereta-u-drumskom-saobracaju and

Roads network in Serbia https://www.putevi-srbije.rs/index.php/en/referentni-sistem-eng or https://cloud.gdi.net/smartPortal/SRBRefSistem

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[15] https://webgate.ec.europa.eu/single-market-compliance-space/home

[16] ADR 2025 – Agreement concerning the International Carriage of Dangerous Goods by Road Chapters 9.1.2.3, 6.11.5.3.2, 4.1.1.12, United Nations, 2024.

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PROFESSIONAL PAPER

Electric vehicle battery safety

Snežana Petković
Prof. dr, Univerzitet u Banjoj Luci, Mašinski fakultet, Banja Luka, Republika Srpska (BiH), snezana.petkovic@mf.unibl.org

Jelena Adžić
Asistent, Univerzitet u Banjoj Luci, Mašinski fakultet, Republika Srpska (BiH), jelena.adzic@mf.unibl.org

Marko Dujaković
Dipl. inž. mašinstva, Univerzitet u Banjoj Luci, Mašinski fakultet, Republika Srpska (BiH), marko.dujakovic@student.mf.unibl.org

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Abstract: One of the main contributors to air pollution is road traffic, primarily due to the emission of harmful gases and particles generated by the combustion of fossil fuels. As a professional response to this issue, the development and implementation of electric vehicles, considered an environmentally friendly alternative, is increasingly being promoted. However, despite their growing presence in traffic, certain safety aspects of electric vehicles still remain insufficiently explored. The main challenge associated with these vehicles is the battery, specifically lithium-ion batteries, which are most commonly used in electric vehicles. In addition to their weight and limited capacity, a particularly concerning issue is the risk of fire and the occurrence of thermal runaway within the battery cells, where an uncontrolled heating process takes place. Extinguishing such fires is extremely difficult, as the battery can reignite even after the flames have been suppressed. This paper provides an analysis of the causes leading to fires within electric vehicle batteries. Using previous research studies, the mechanism of fire development is explained — from the initial battery cell damage, the phenomenon of thermal runaway, smoke occurrence, all the way to explosion. The paper also presents both internal and external strategies for improving the safety of electric vehicles, with special emphasis on minimizing human error in order to prevent severe consequences, including battery explosion. To ensure that lithium-ion batteries and their components meet specific safety requirements, numerous safety standards and testing methods have been developed, which are briefly outlined in the paper.

Key words: Electric vehicles, batteries, thermal runaway, fire, explosion.

INTRODUCTION

Lithium-ion batteries, as rechargeable energy-storage systems, represent the dominant technology used in electric and hybrid vehicles, with an estimated market share of approximately 60% to 66% of all installed battery systems worldwide (*IEA Global EV Outlook 2023*). All sub-types of lithium-ion batteries share the same basic structure, consisting of a large number of galvanic cells. Each individual cell contains a cathode, an anode, an electrolyte, and a separator (Figure 1). These subtypes primarily differ in the chemical composition of the active material in the cathode coating, with three variants being the most widely used: lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (NMC), and lithium nickel cobalt aluminum oxide (NCA). Due to their distinct properties, these variants are used in different categories of vehicles.

The operating principle of all lithium-ion battery types is the same. During charging, an external energy source drives lithium ions (Li^+) to de-intercalate from the cathode, diffuse through the electrolyte, pass through the nanopores of the separator, and intercalate into the graphite material on the anode. To maintain electrical balance, electrons simultaneously flow in the opposite direction through the external circuit, from the anode to the cathode. During discharge, Li^+ ions spontaneously migrate from the anode back to the cathode, releasing electrical energy to the load. Ion transport during charge–discharge cycling generates significant heat as a result of Joule heating and the chemical processes involved in the cycle.

The heat produced by electrochemical reactions is a normal phenomenon during nominal battery operation and does not pose a safety risk as long as it is dissipated evenly and efficiently. However, during operation, external influences, manufacturing defects, or undesirable charging and discharging conditions may cause excessive heat generation that cannot be removed in a timely manner, leading to safety hazards. Different cell geometries (cylindrical, prismatic, pouch, etc.) exhibit different safety characteristics, with cylindrical cells generally considered the safest.

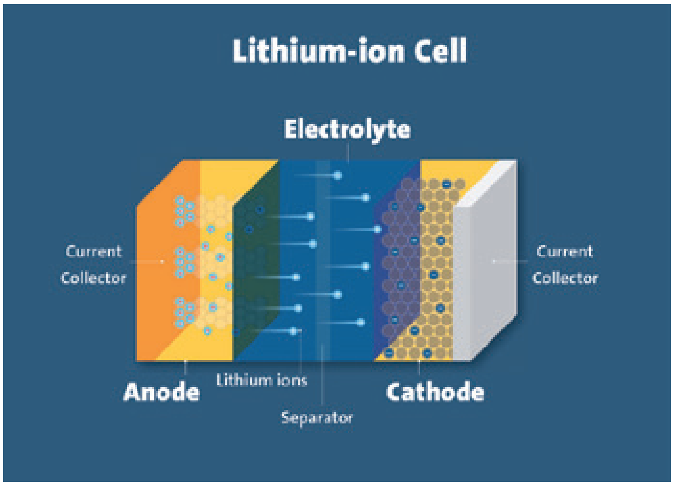


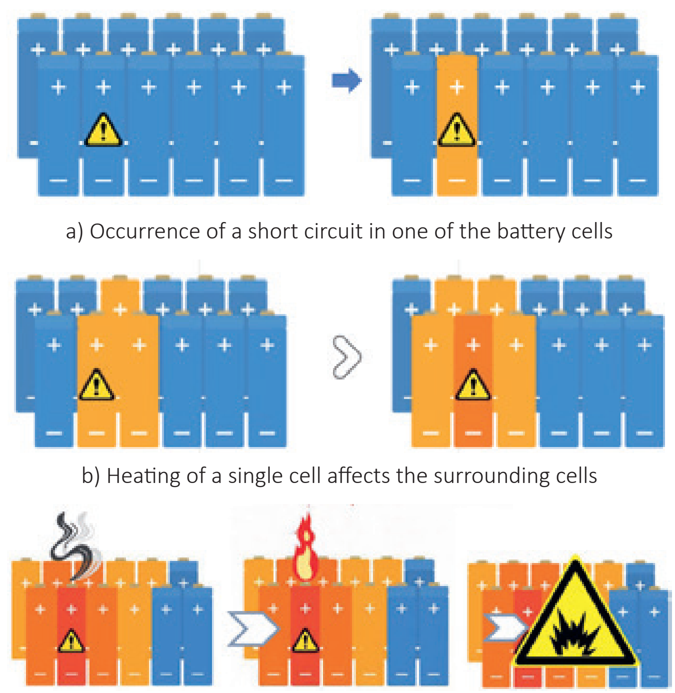
Figure 1. Basic element of a lithium-ion battery (https://ul.org/research-updates/what-are-lithium-ion-batteries)

SAFETY ISSUES IN ELECTRIC VEHICLES

Even under normal operating conditions, the heat generated within a battery cannot be completely removed, particularly in large battery packs and during operation in high ambient temperatures (K. Amine et al., 2010). As the battery temperature increases, additional undesirable parasitic chemical reactions may occur, leading to **thermal runaway**, a state in which the heat generation inside the battery becomes uncontrollable (Wang et al., 2012). The causes of thermal runaway are various forms of battery damage, which are especially likely to occur during traffic accidents. Such damage may include mechanical damage to the battery (housing deformation, compression, puncture, or twisting of cells), electrical damage (overcharging/discharging or short circuits), as well as thermal damage (thermal shock or localized heating), as shown in Figure 2. Understanding battery performance under hazardous operating conditions is essential for improving battery safety during their development and manufacturing processes.

Thermal Runaway

Thermal runaway is a phenomenon representing the greatest risk to the thermal stability of lithium-ion batteries (Feng et al., 2017). The stages of thermal runaway development are shown in Figure 3. If any form of internal cell damage occurs, the normal electrochemical reactions are replaced by undesirable chemical processes. Under such conditions, heat accelerates exothermic reactions, resulting in the generation of even larger amounts of heat and the formation of gases. When the abnormal and rapidly increasing amount of heat cannot be dissipated, the materials from which the battery is constructed become chemically unstable and begin to undergo exothermic chemical reactions



a) Occurrence of a short circuit in one of the battery cells

b) Heating of a single cell affects the surrounding cells

c) Onset of thermal runaway accompanied by black and white smoke

d) Ignition or explosion of the cell

Figure 3. Stages of thermal runaway development

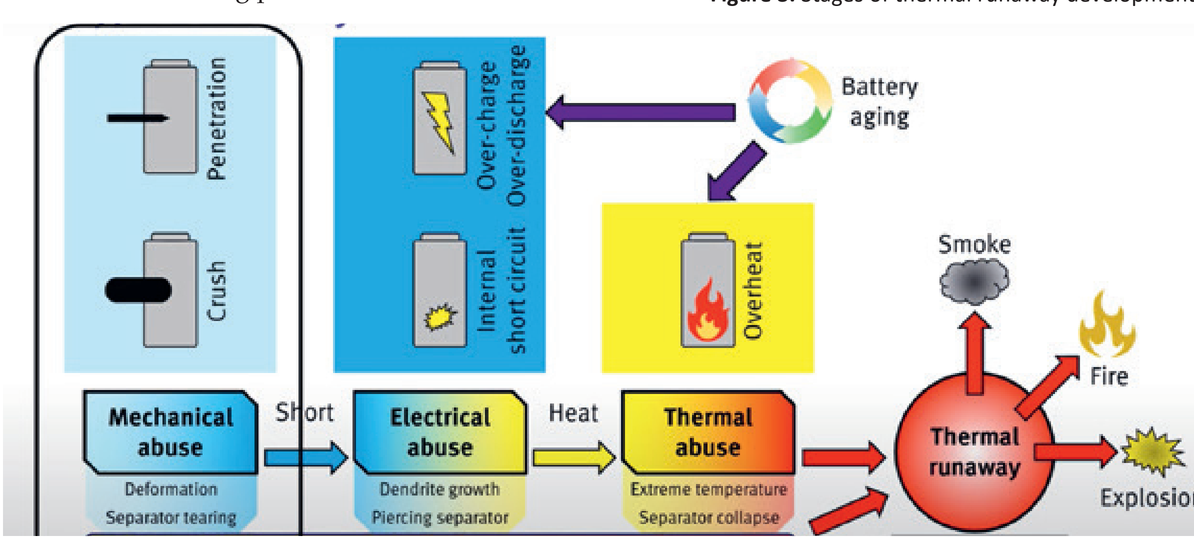


Figure 2. Causes of battery thermal runaway (https://www.batterydesign.net/battery-fires/)

These uncontrolled and unstable chemical reactions, which are extremely difficult to bring under control, eventually lead to the breakdown of the separator structure, allowing direct contact between the electrodes. This results in an internal short circuit and a rapid increase in temperature, a phenomenon known as thermal runaway.

In the initial stage, particles of heavy-metal dust from the cathode may appear in the form of dark smoke, followed by the release of a white smoke cloud. The presence of white smoke indicates that the released gases carry fine droplets of the electrolyte solvent. As oxygen from the surrounding environment mixes with this white smoke and heat accumulation continues, the battery cell may ignite, causing the fire to spread to neighboring cells. Ignition typically occurs within a few seconds to a few minutes after the appearance of the white smoke cloud. Under certain conditions, the white smoke cloud—containing toxic and flammable gases—may unexpectedly explode, posing a severe hazard to the surrounding area.

Problems Caused by Mechanical Damage

As the number of electric vehicles on the roads continues to grow, the likelihood of traffic accidents involving electric vehicles has also increased, thereby raising the probability of mechanical damage to batteries. In a moving vehicle, the battery is subjected to significant forces, which in extreme cases, such as a collision, can cause severe damage. When the battery casing is compromised, air can directly enter the battery system, leading to undesirable reactions with the active components and electrolytes. Due to the high energy density of lithium-ion batteries, such damage can release a significant amount of heat, potentially triggering thermal runaway. Even when the casing is only deformed, the internal components of the battery can be severely damaged: metal current connectors may break, and separators with insufficient flexibility may fail, resulting in direct contact between the electrodes (short circuit). If the heat generated by this short circuit is high, the energy density is sufficient to trigger additional internal short circuits in the surrounding area, inevitably leading to thermal runaway throughout the battery.

The battery casing serves as the first level of protection and must be sufficiently robust to withstand mechanical forces without failure. Its primary role is to ensure that the internal structure of the battery remains intact under certain deformation conditions. The mechanical behavior of the casing represents the most vulnerable point during safety incidents, making it essential to conduct detailed analyses during the design process and the selection of materials for lithium-ion battery enclosures.

Problems Caused by Electrical Damage

When a battery experiences overcharging, over-discharging, or an external short circuit, it is subjected to electrical stress, which triggers a series of undesirable electrochemical reactions within the cell. The mechanisms of overcharging and over-discharging are similar, while an external short circuit occurs when the cathode and anode of the same cell come into direct contact through a conductor. Overcharging represents the most hazardous type of electrical damage. If the battery management system cannot effectively monitor the voltage of each individual cell, there is a significant risk of overcharging. Since all excess energy is stored within the battery, overcharging is extremely dangerous, leading to a substantial increase in the internal temperature of the battery. Although batteries are typically charged up to a specific **State of Charge (SOC)**, some cells may have a higher SOC at the beginning of the charging process, making them more susceptible to overcharging.

The stages of battery overcharging can be described as follows, as illustrated in Figure 4:

- **Phase I:** The battery voltage steadily rises and exceeds the nominal cutoff voltage, marking the start of the overcharging process (Figure 4a).
- **Phase II:** When the battery is overcharged by approximately 1.2 V above full charge, side reactions begin to occur within the cell (Figure 4b).
- **Phase III:** The battery temperature continues to rise more rapidly, and the battery begins to swell due to gas formation (Figure 4c).
- **Phase IV:** The battery casing ruptures, causing damage to the separator and initiating thermal runaway in the lithium-ion battery (Figure 4d).

The charging rate is often the most significant factor influencing the risk of overcharging. The current density during overcharging directly determines the rate of heat generation resulting from chemical reactions within the battery: the higher the current, the greater the amount of heat produced per unit time, thereby increasing the risk of uncontrolled battery behavior.

Problems Caused by Thermal Damage to Batteries

Thermal damage to a battery occurs when the battery

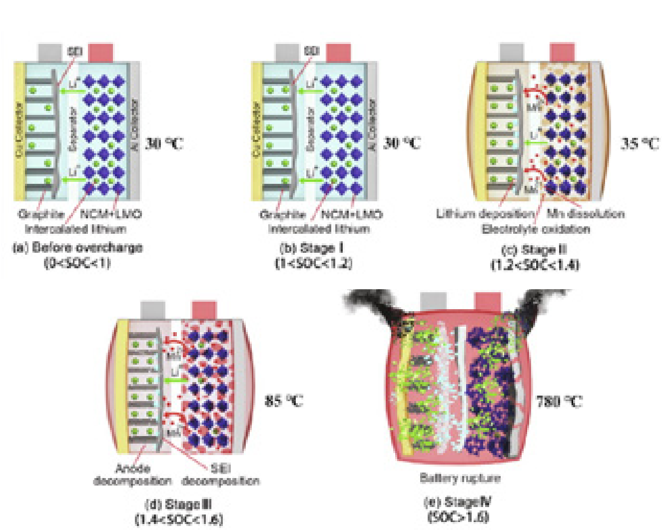


Figure 4. Stages of lithium-ion battery overcharging, (Chen et al., 2021)

reaches high temperatures or experiences thermal shock, potentially leading to fire (Wang et al., 2019). Battery fires can occur during the charging of electric vehicles, as described in the previous section, or as a result of exposure to flames—for example, if nearby vehicles are on fire or if flammable materials such as highly combustible pollen, seeds, flowers, or leaves are present in the air. These materials may ignite when in close proximity or in direct contact with a heated or malfunctioning battery.

In theory, normal cycling of a battery cannot cause safety incidents, as the heat generated during standard anodic and cathodic reactions is insufficient to trigger a sudden temperature rise. However, in practice, the rate of heat release from the electrodes often exceeds the rate at which heat can be dissipated (cooling). Poor battery design can lead to uneven heat transfer and non-uniform temperature distribution, increasing the risk of thermal shock. Localized high temperatures can trigger exothermic reactions, potentially leading to battery explosions. Heat transfer within a battery primarily depends on the external surface area and the battery's geometry.

Electric Vehicle Fires

The causes of fires in electric vehicles (EVs) are diverse and complex. Statistics from Australia indicate that approximately **15% of all EV battery fires occur while the vehicles are connected to a charger or within one hour after disconnection from charging**. It is important to emphasize that battery charging itself cannot be considered the primary cause of these fires, even though EVs spend a significant portion of their operational life connected to a charger. Research has shown that most fires of this type occur due to **pre-existing battery damage**, rather than a failure of the charger or overcharging.

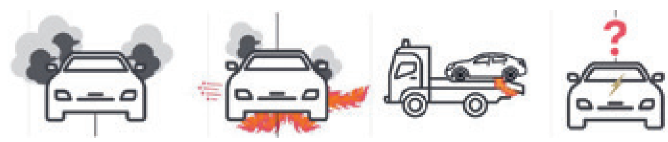
The main factors leading to battery damage, and consequently to potential fires, include:

- **Collision:** Traffic accidents can cause significant damage to the battery. Additionally, driving over sharp objects on the road can physically damage the battery.
- **Water immersion:** Prolonged exposure of the vehicle to water, particularly saltwater or floodwater, can lead to corrosion and internal short circuits within the battery system. Seawater is especially hazardous due to its conductivity, which can trigger chemical reactions and lead to thermal runaway.
- **Manufacturing defects:** If manufacturers later identify issues in a battery that could potentially cause thermal runaway, they are required to recall these products, as the risk of fire in such vehicles is significant.
- **External fire:** If the vehicle is exposed to an external fire, flames can spread to the vehicle and involve the battery.

Less common causes of fires include faulty cables, defective charging cords, or failures in the electrical system.

Although there are some similarities with fires in internal combustion engine vehicles, lithium-ion battery fires in EVs present additional challenges, as shown in Figure 5:

- The release of a toxic cloud of flammable gases, posing both respiratory and explosive hazards,
- The occurrence of thermal runaway, which complicates extinguishing the battery fire,
- The risk of **re-ignition** even after the fire appears to be extinguished, and
- EV battery fires are still not fully understood, requiring emergency response teams to receive specialized training for handling fires in electric vehicles.



I II III IV

Figure 5. Challenges for emergency response teams

During thermal runaway in electric vehicle batteries, three main hazards are present:

- **Gas release** – Rapid heating of lithium-ion cells causes electrolyte evaporation, resulting in the release of a toxic and flammable gas cloud.
- **Ignition** – After gas release, the flammable gases can ignite. The vapor pressure escaping from the battery often forms a directed jet flame, making extinguishing difficult and allowing the fire to spread rapidly.
- **Explosion** – When gases cannot escape from the battery pack (e.g., due to a sealed casing or blockage), they can accumulate under high pressure, creating a risk of an explosion of the entire gas cloud, which can have catastrophic consequences for both the vehicle and its surroundings.

When handling, transporting, or repairing electric vehicle batteries, the following points should be considered:

- **Lower State of Charge (SOC) reduces fire risk:** Batteries with a lower SOC have a lower likelihood of fire. A battery with a SOC below 50% has a reduced probability of entering thermal runaway, although gas release without ignition may still occur. Therefore, for transport purposes, it is recommended that electric vehicle batteries be charged to **30% SOC or less**.
- **No lithium-ion battery is fireproof:** All batteries used in electric vehicles can experience thermal runaway, regardless of chemical composition or form. While design and chemistry can influence the likelihood or rate of thermal runaway propa-

gation, they cannot fully prevent it.
- **Battery behavior during fire varies:** The chemical composition and shape of the battery can affect the volume of smoke, flame intensity, and the potential for explosion.
- **High risk to emergency responders:** In the event of an electric vehicle fire, first responders face significant hazards. It is therefore critical that emergency personnel identify the vehicle as electric upon arrival at the scene.

STRATEGIES FOR IMPROVING THE SAFETY OF ELECTRIC VEHICLE BATTERIES

The safety of lithium-ion batteries is one of the key factors determining the future widespread adoption of electric vehicles. Improving the safety of lithium-ion batteries involves:

- **Internal strategies**, which focus on the materials and design of the battery to prevent excessive heat generation.
- **External strategies**, which relate to the efficiency of cooling and cell balancing, both of which are essential for enhancing battery safety and longevity.
- **Battery testing and monitoring systems,** which are critical for ensuring safe operation under various service conditions.

Internal Strategies

Enhancing active materials, separators, and electrolytes can significantly improve safety performance. This is determined by a range of factors, including the chemical composition of the active material, the type of electrolyte, the efficiency of heat generation and dissipation, and tolerance to external mechanical stresses. The most easily controlled factors within the battery itself include the percentage of active electrode materials, electrolyte composition, and separator characteristics.

Cathode materials in lithium-ion batteries must exhibit chemical and structural stability to ensure safe operation throughout charge–discharge cycles. Separators are crucial for preventing short circuits in batteries and must maintain thermal stability and mechanical integrity. In anodes, lithium plating presents significant safety risks, particularly under potential thermal and electrical damage. The flammability and stability of the electrolyte are also critical factors. Organic carbonate-based liquid electrolytes are highly flammable and can lead to combustion or explosions under adverse conditions. Improving the flash point or decomposition temperature of the electrolyte can greatly enhance safety. Solid-state electrolytes are being developed to eliminate many of the undesirable effects associated with liquid electrolytes.

External Strategies

Effective cooling strategies and cell voltage balancing are essential for improving the safety and longevity of batteries.

Balancing the voltage between cells is crucial for minimizing differences within the battery pack. Both passive and active equalization methods are used to maintain cell balance. Passive balancing can dissipate excess energy from overcharged high-capacity cells within the battery, but it cannot supply energy to undercharged low-capacity cells. The circuit structure used in passive balancing systems is relatively simple, and the energy-consuming components can continuously dissipate energy. Active balancing, on the other hand, involves the use of various circuit topologies and control strategies that non-dissipatively transfer energy between different cells and modules, thereby equalizing the system (storing energy from high SOC cells and charging low SOC cells). Active methods demonstrate higher efficiency.

Operating at high temperatures significantly accelerates battery aging, which directly leads to safety issues such as thermal runaway. Therefore, a well-designed and integrated cooling system is a critical safety factor for these batteries, enabling precise temperature control. The optimal operating temperature range for lithium-ion batteries is between **15 °C and 35 °C** (Chen et al., 2021). An efficient cooling system must be capable of maintaining this temperature range, thereby extending battery life and reducing maintenance costs.

Some of the battery cooling systems are:

- **Air cooling system** – the simplest and least expensive option; less efficient and suitable for smaller battery packs.
- **Liquid cooling system (water, glycol)** – the most widely used method in electric vehicles due to its high efficiency and precision.
- **Phase change material (PCM)-based cooling system** – these materials absorb heat by changing their phase, providing passive cooling; still under investigation for mass application.
- **Heat pipe-based temperature management system** – heat pipes use phase transitions of the working fluid for highly efficient heat transfer and are also under study for future application.

Among all these systems**, liquid cooling** is the most widely used in electric vehicles due to its significant advantages:

- **High specific heat** – absorbs significantly more heat per unit mass, making the system much more efficient.
- **Better thermal conductivity** – transfers heat more effectively compared to air.
- **Good temperature control** – maintains battery temperature within the optimal range, directly extending battery life, improving vehicle performance, and ensuring safety.
- **Even temperature distribution** – liquids provide more uniform cooling of all cells within the bat-

tery pack.

- **Design adaptability** – although requiring more components than other systems, it can be efficiently integrated into the vehicle design.

Battery Testing and Monitoring Systems

Before being installed in a vehicle, every lithium-ion battery must undergo a rigorous series of tests to determine its safety. Safety standards and tests ensure that the battery and its components meet the prescribed criteria, particularly for commercial production. Electric vehicle batteries must be certified in accordance with relevant safety standards before mass production and sale. Testing of certified and standardized batteries provides customers with assurance that the risk of thermal runaway under specified conditions is minimized.

A large number of countries and international organizations have developed safety-oriented standards for electric vehicle batteries, including: the Chinese standard **GB/T 31485,** the **Society of Automotive Engineers (SAE) Standard 2464,** the **International Electrotechnical Commission (IEC) Standard IEC62133 Edition 2.0,** the **United Nations (UN) Standard UN38.3,** the **Japanese Industrial Standard (JIS) C8714,** the **Underwriters Laboratories (UL) Standard UL2580 Edition 2.0,** and the **International Organization for Standardization (ISO) Standard ISO 16750–2.** In addition to standard tests, each standard includes specific testing methodologies (Chen et al., 2021).

The main tests that every lithium-ion battery must undergo include:

- **Test 1 (electrochemical performance):** overcharging, over-discharging at high and low temperatures, external short circuit, and forced discharge.
- **Test 2 (mechanical properties):** drop test, high-impact test, nail penetration.
- **Test 3 (thermal performance):** heating, thermal shock, and spark exposure.
- **Test 4 (environmental conditions):** low pressure, high altitude, and vehicle submersion.

Laboratory testing conditions are generally more severe than real-world driving conditions to ensure maximum safety during vehicle operation. Although the tests are extremely rigorous and batteries undergo complex procedures during certification, battery fires still remain a challenge for electric vehicles. Therefore, continuous optimization and improvement of pre-installation testing procedures are necessary to ensure the highest possible safety of batteries before they are integrated into vehicles.

CONCLUSION

In recent years, energy and environmental issues have become increasingly prominent, and electric vehicles powered by lithium-ion batteries have demonstrated significant potential and advantages in addressing these challenges. Compared to other battery types, lithium-ion batteries offer high specific energy, high energy density, good durability, low self-discharge, and a long lifespan.

However, battery temperature management has become a significant challenge for manufacturers. At high temperatures, lithium-ion batteries can experience thermal runaway, leading to short circuits, combustion, explosions, and other safety hazards. At low temperatures, lithium dendrites may form, causing short circuits, failure to start, and other operational malfunctions.

The solution lies in careful design, efficient temperature management, and rigorous battery testing. Batteries must be designed to maintain their performance under various operating conditions that may occur during their service life. Continuous improvement of cooling systems, along with ongoing optimization of safety standards and testing procedures, is imperative for enhancing battery safety and reliability.

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REVIEW SCIENTIFIC PAPER

Training of professional drivers under current regulatory conditions

Saša Zdravković
Viši stručni saradnik, dipl. inž. saobraćaja, Agencija za bezbednost saobraćaja, Beograd, Republika Srbija, sasa.zdravkovic@abs.gov.rs

Radovan Višković
Dipl. inž. saobraćaja, Saobraćajni fakultet Doboj, Univerzitet u Istočnom Sarajevu, Doboj, Republika Srdpska, radovanviskovic1964@gmail.com

Pavle Gladović
Prof. Dr, dipl. inž. saobraćaja, Fakultet tehničkih nauka, Novi Sad, Republika Srbija, anaipavle@gmail.com

Ksenija Zdravković
Vodeći administrator, master ekonomista, AMCC Centar za motorna vozila, Beograd, Republika Srbija, ksenija.zdravkovic@yahoo.com

Snježana Rajilić
Prof. dr., dipl. inž. saobraćaja, Panevropski univerzitet "APEIRON", Banja Luka, BiH, snjezana65.rajilic@gmail.com

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Abstract: The aim of this paper is a comparative analysis of the impact of contemporary regulatory changes in the European Union and the Republic of Serbia on the training system for professional drivers of commercial vehicles, with an emphasis on their role in improving road traffic safety. Particular attention is given to the evolution of the regulatory framework in the period 2003–2022, from Directive 2003/59/EC to Directive 2022/2561/EC, which advances the system through the digitalization of teaching, the promotion of environmentally responsible and safety-oriented driving, and the application of more flexible learning methods. The research is set within the context of the global initiative Second Decade of Action for Road Safety 2021–2030, whose goal is to reduce the number of road traffic fatalities by at least 50% (United Nations, 2021). The starting hypothesis of the paper is that the alignment of the national training system with European standards significantly contributes to the improvement of road transport safety and efficiency. The research is based on descriptive, analytical, comparative, and synthetic methods, supplemented with statistical indicators and case study analysis. Special emphasis is placed on the challenges of harmonizing the national training system with European standards—institutional, technological, and pedagogical–andragogical. Based on the analysis, recommendations have been formulated aimed at strengthening intersectoral cooperation, modernizing training programs, and supporting the continuous professional development of drivers, thereby contributing to the creation of safer and more competent road users.

Key words: road safety, driver competencies**,** driver training, professional drivers, regulatory framework.

INTRODUCTION

Professional drivers of commercial vehicles represent one of the key categories of participants in the road traffic, as their competencies directly influence the safety, efficiency, and sustainability of the transport system (Road Traffic Safety Agency [RTSA], 2022). In the context of dynamic changes in the transport policies of the European Union (EU) and the Republic of Serbia, the quality of initial and periodic driver training gains strategic importance.

Modern regulatory frameworks, such as Directive 2003/59/EC, guide the training of professional drivers through standardized programs and a minimum number of training hours, with the aim of improving road traffic safety (European Commission, 2003).

By adopting Directive 2003/59/EC, the European Union established uniform standards for the initial and periodic training of professional drivers, emphasizing professional competence as a prerequisite for safe and efficient driving (European Commission, 2003). Directive 2022/2561/EC further strengthens this framework by introducing digitalized training processes, promoting environmentally responsible and safety oriented driving, and enabling more flexible learning methods tailored to adult learners (European Commission, 2022). These changes carry significant institutional, pedagogical, and andragogical implications.

At the global level, these reforms align with the United Nations initiative "Second Decade of Action for

Road Safety 2021–2030," which aims to reduce the number of road traffic fatalities by at least 50% (United Nations, 2021). The initiative emphasizes a systemic and intersectoral approach to road traffic safety, within which professional drivers play a key role.

In the Republic of Serbia, the process of harmonizing national regulations with European standards is accompanied by a number of challenges, particularly concerning institutional capacity for implementing modern instructional models, the technological infrastructure required for digitalization, and methodological adjustments specific to adult education (European Commission, 2025; Zdravković, 2025). Although there is awareness of the importance of modernizing the system, practice shows a continued need for additional investments in training programs, personnel, and methods of continuous professional development for drivers (Zdravković, 2025).

Based on the above, the aim of this paper is to analyze the impact of contemporary regulatory changes on the professional driver training system, with emphasis on the institutional, technological, and pedagogical-andragogical aspects of their implementation in Serbia. The scientific contribution lies in the comparative analysis of European and national training models, the identification of implementation challenges, and the formulation of recommendations for improving instructional practice and road traffic safety policies (European Commission, 2022; United Nations, 2021)

MATERIALS AND METHODS

The research is based on a systematic analysis of domestic and international literature, with emphasis on online sources and relevant professional publications (Elvik & Vaa, 2021; European Commission, 2003; ABS, 2022). Special attention was given to legal regulations from both national and international legislation, focusing on the (EU27) countries and the analysis of directives governing the training of professional drivers (European Commission, 2022). Additional data were drawn from reports issued by national and international institutions on road traffic accidents, as well as from quality and safety management standards, primarily ISO 9001 and ISO 39001 (Johansson, 2012).

The following methods were applied in the research:

- **Descriptive method** – used to describe phenomena and processes within professional driver training models in EU27 member states and in the Republic of Serbia, as well as to outline guidelines for their improvement.
- **Analytical method** – used to analyze existing models and the state of road traffic safety in the observed countries.
- **Comparative method** – used to compare training models and statistical indicators of road traffic safety.
- **Synthetic method** – used to integrate results and connect training models with safety indicators for commercial vehicle drivers.
- **Statistical method** – used to analyze quantitative data on traffic accidents, driver performance, and the effectiveness of instructional models.

In addition, the results of initial and periodic training were analyzed, including examination outcomes, candidate evaluations on standardized tests, as well as the results of seminars and other continuous professional development programs (Zdravković, 2025; European Commission, 2025). This approach provided a comprehensive overview of the impact of regulatory changes on the training system and the competencies of professional drivers, with particular emphasis on driving safety and quality. A limitation of the study is the insufficient number of empirical studies on the effects of the new directives in Serbia, which necessitates reliance on comparative and indirect indicators.

RESULTS

The research showed that the evolution of the EU regulatory framework, through Directive 2003/59/EC and its amendment 2022/2561/EC, has a significant impact on the quality of professional driver training and road-traffic safety. Although the directives establish standards for qualification and periodic training, a unified system for evaluating learning outcomes is still lacking, as is precise regulation regarding instructional personnel and teaching methodologies. This highlights the need for improved harmonization of training systems, the application of digital and flexible learning methods, and continuous evaluation processes to monitor the level of competencies achieved (European Commission, 2003; European Commission, 2022).

Evolution of the EU Regulatory Framework

The historical development of regulations governing the training of professional drivers in the European Union began with the adoption of Directive 76/914/EEC (Council of the European Communities, 1976), which initiated the process of standardizing qualifications. Although training initially had a recommended (non-mandatory) character in most countries, states such as France and the Netherlands introduced compulsory programs, reflecting their early recognition of the importance of systematically developing professional competencies. Due to global socio-economic changes during the 1980s, an increased demand for transport services emerged, along with a simultaneous shortage of qualified drivers, which negatively affected road traffic safety and efficiency.

The publication of the White Paper on Transport (European Commission, 1992) marked the beginning of transport market liberalization within the EU and highlighted the importance of professional driver competencies for traffic safety. Standardization of training continued with Directive 2003/59/EC, which introduced mandatory initial and periodic training (CPC), focusing on safe driving and harmonized criteria across the EU (European Commission, 2003). Directive 2022/2561/EC further expanded the framework by incorporating digital technologies, flexible learning methods, and the promotion of environmentally responsible driving tailored to adult learners (European Commission, 2022).

Besides regulatory measures, the ISO 39001 standard also makes a significant contribution to road traffic safety by improving systemic road traffic safety management. A study conducted in 141 companies in Sweden showed that 40% of organizations achieved financial benefits, while 72% assessed the implementation of the standard as highly effective (Johansson, 2012), which supports the long term vision of the European Commission for "zero fatalities by 2050" (European Commission, 2011).

Although the regulatory framework contributes to improving safety, its effectiveness is limited due to insufficiently precise definitions of learning outcomes and weak integration of digital tools and driver-assistance systems (Sullman, Dorn & Niemi, 2021; Samuel & Rowe, 2023; Silla & Laitinen, 2023). Simulation-based and situational training show potential for the development of cognitive and psychomotor skills, but convincing evidence on their long-term impact on reducing accident risk is still lacking.

One of the key challenges in the professional driver training system is the absence of systematic evaluation of training outcomes and their impact on driver behavior under real-world traffic conditions (Elvik & Vaa, 2021). Research indicates that the application of driving simulators remains limited and insufficiently integrated into risk-management strategies (Murray & Watson, 2023), while the lack of continuous instructor development leads to a predominant focus on exam preparation rather than on cultivating a safety culture and defensive driving styles (Watson-Brown, Scott-Parker, Simons-Morton & Senserrick, 2020).

Despite these limitations, European directives and standards have significantly contributed to improving professional training and enhancing road traffic safety, providing a foundation for adaptation and advancement of training within national contexts, such as Serbia (European Commission, 2003, 2022). Continuous evaluation and monitoring of acquired competencies remain essential for further development of the system.

Analysis of the Regulatory Framework in Serbia

The national framework for the training of professional drivers in the Republic of Serbia has been developing gradually, with increasing alignment to the regulations and standards of the European Union. Based on its own road safety priorities and EU recommendations, Serbia adopted a new Road Traffic Safety Act in 2009 (Road Traffic Safety Act, 2009, Article 203), establishing the foundation for structuring a professional driver training system.

Key developments followed in 2018 with the adoption of two by-laws:

- Rulebook on the Conditions and Method for Obtaining a Certificate of Professional Competence and the Driver Qualification Card (Official Gazette of the Republic of Serbia, No. 102/2018), and
- Rulebook on the Requirements for Legal Entities Providing Professional Driver Training (Official Gazette of the Republic of Serbia, No. 102/2018, 29/2025).

These regulations represent the core legislative instruments that define the standards, organizational requirements, and certification procedures for the professional training of commercial drivers in Serbia.

These by-laws introduced mandatory training and examination for acquiring professional competence. Drivers who had obtained licenses for categories C1, C1E, C, CE, D1, D1E, D, and DE by 30 December 2019 were granted recognition of their existing rights, in accordance with Directive 2003/59/EC (Directive 2003/59/EC, 2003, Article 4).

The training model in the Republic of Serbia is largely aligned with Directive 2003/59/EC. It prescribes mandatory training of a specified number of hours and examinations, with exceptions for drivers holding recognized rights. The system includes standard and accelerated programs, as well as additional training for qualification upgrades, similarly to Article 5(5) of Directive 2003/59/EC.

The types of mandatory training include:

- **Initial training** – at least 280 teaching hours,
- **Accelerated initial training** – at least 140 teaching hours,
- **Additional training** – at least 70 teaching hours,
- **Additional training** (shortened) – at least 35 teaching hours.

The main difference between the Serbian and European training models lies in the criterion used to select the program. While the EU links the type of training to the driver's age, Serbia applies an educational-level criterion: drivers with at least three years of secondary education attend accelerated training, whereas others complete the full 280-hour program. Specifically, drivers who have completed at least three years of secondary education undergo the 140-hour accelerated initial training, while those without this educational level must complete the full 280-hour program (Table 1).

Table 1. Driver Training Model in the Republic of Serbia

License Category	Driving Category	Age for Qualification Access		Education/Number of Training Hours			Additional Training
Freight Transport	C1, C1E, C and CE	C1, C1E	C and CE	Initial – Category II Vehicle	280	70	Passenger Transport
		18	18	Category III and above	140	35	
		/	**18***	Recognized Rights / Driver with Level III Vocational Education*		35	
Passenger Transport	D1, D1E, D and DE	D1, D1E	D and DE	Initial – Category II Vehicle	280	70	Freight Transport
		18	21	Category III and above	140	35	
		/	/	Recognized Rights		35**	

* A driving license for categories C and CE may be obtained by a secondary school student who has completed a diploma program in the Motor Vehicle Driver profile; the initial qualification for freight transport is recognized for such individuals.

** A driver who has exchanged a driving license from another country for a Republic of Serbia driving license, and who had completed category D before 30 December 2019, is granted recognition of acquired rights for passenger transport, while category C was obtained after 30 December 2019.

Note: Data sourced from Zdravković, Gladović, & Zdravković (2022).

Periodic training, in accordance with Article 7 of the Directive, comprises 35 hours of instruction within a five-year cycle (Directive 2003/59/EC, 2003, Article 7). This form of training is also mandatory for drivers with recognized acquired rights.The requirements for instructional staff in Serbia are relatively strict: lecturers were required, at the time of certification, to have at least a Level VII vocational qualification and one year of work experience, while instructors had to possess at least three years of work experience or five years of international experience as drivers holding a Driver Qualification Card. Compared to the Directive, which allows greater flexibility for Member States, the Serbian model is more restrictive (Directive 2003/59/EC, 2003).Amendments to the Law in 2025 introduced significant changes: training is no longer mandatory for all participants, except for young drivers obtaining licenses before the age of 21.

Additionally, the validity of the Driver Qualification Card was extended to seven years for licenses issued until 31 December 2020, removing the obligation to attend five interim seminars (Law on Amendments and Supplements to the Road Traffic Safety Act, 2025).

Although these measures reduce costs and administrative burdens, they raise concerns regarding the continuity of professional education and the control of driver competencies. The closure of training centers and the reduction of training programs may have a negative impact on road-traffic safety.

In contrast, Directive 2022/2561/EC emphasizes the importance of standardized programs, digitalization of instruction, support for teaching staff, and environmentally responsible driving (European Commission, 2022), providing guidance for the further development of the system in Serbia.

Statistical Trends

Alignment of the training system with European standards demonstrates a significant impact on reducing the number of road-traffic accidents. While EU countries report a stable decline in accident numbers, Serbia shows

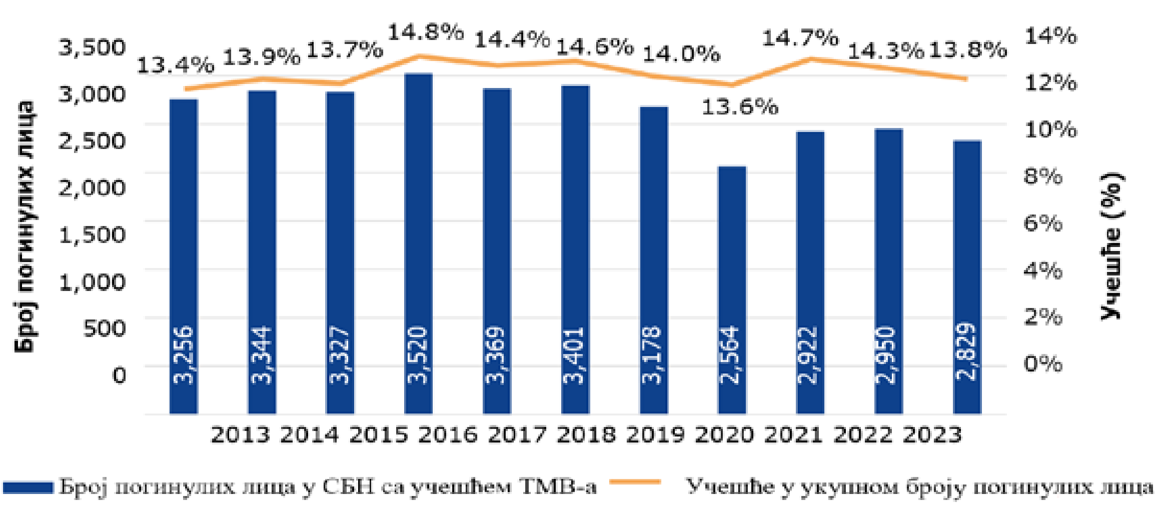

Figure 1. Annual Number of Fatalities in Accidents Involving HGVs and Their Share of Total Fatalities in the EU27 (2013–2023).

Source: European Commission, 2025

positive, but slower trends (European Commission, 2025; Schindler, Smith & Müller, 2022). According to data from the European Commission (2025), heavy goods vehicles (HGVs) are involved in approximately 4–5% of accidents in EU countries, but are responsible for roughly 14% of fatalities (see Figure 1).

Similar issues are observed in the field of passenger transport, where buses are involved in 2% of all fatal road-traffic accidents, with victims frequently being pedestrians (25%) (European Commission, 2025; see Figure 2). These data highlight the need for more intensive and higher-quality training, with a particular focus on the protection of vulnerable road users.

Directive 2022/2561/EC establishes the minimum requirements for obtaining professional driving licenses for categories "C" (18 years) and "D" (21 years) following completion of the prescribed training, thereby directly linking the acquisition of professional driving categories to vocational qualifications. At the same time, EU strategic documents emphasize the importance of digitalization of driving licenses, harmonization of training standards, assessment of psychophysical abilities, and continuous improvement of training to enhance safety and driving quality across all Member States (European Commission, 2018, 2020, 2022, 2023).

The objective is to ensure a unified and transparent system of training and certification that strengthens the safety culture, standards of instructional staff, and driver competencies across the European Union, in line with the "Vision Zero" concept and the medium-term targets for reducing fatalities and serious injuries by 2030 (European Commission, 2019; European Commission, 2022).

According to available data from the Road Traffic Safety Agency of the Republic of Serbia, between 2017 and 2021 there were 640 fatal accidents (FA) involving commercial vehicles (freight vehicles and buses) and 13,238 accidents involving commercial vehicles with injured persons (IA). Accidents involving commercial vehicles with fatalities account for **26% of all fatal road-traffic accidents**. In these accidents, 734 people were killed and 21,015 were injured, **representing approximately 27% of all fatalities** (FA) and 21% of **all injured persons** (IA) in road-traffic accidents (Road Traffic Safety Agency [ABS], 2022).

Of the total number of fatalities in accidents involving commercial vehicles, 623 people (85%) were killed in accidents involving at least one freight vehicle, 128 people (17%) in accidents involving at least one bus, and 17 people (2%) in accidents involving both a truck and a bus ([ABS], 2022).

These data confirm that professional drivers and commercial vehicles have a significant impact on road safety. While the EU records a decline in accidents due to standardized training, Serbia shows a slower but positive trend. Despite the lower involvement of commercial vehicles in the total number of accidents, these vehicles cause a disproportionately high number of fatalities, particularly among vulnerable road users. This indicates the need for Serbia to improve its training system in line with European standards, using digital tools and flexible educational approaches. Alignment with Directive 2022/2561/EC is crucial for reducing the most severe accidents and enhancing road safety.

Research Results on the effectiveness of periodic training for professional drivers in Serbia

The study encompassed 4,193 professional drivers who possessed an initial qualification obtained either through basic training or through recognition of acquired rights. The effectiveness of periodic training was assessed through a comparative analysis of pre- and post-test results during a single cycle of five thematic seminars, with each test containing 20 questions with four possible answers.

The analysis demonstrated a statistically significant improvement in knowledge across all examined

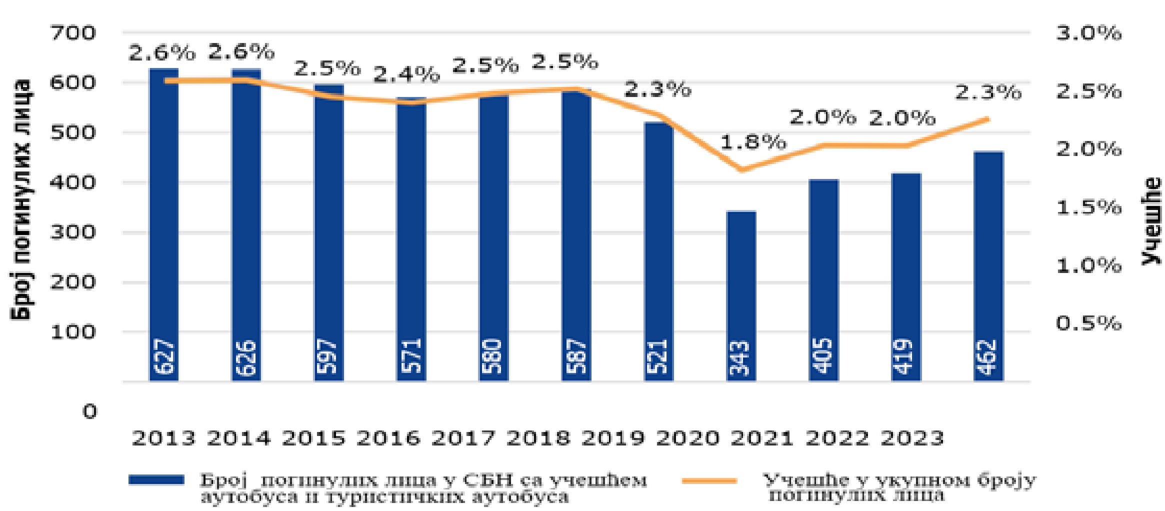

Figure 2. Annual Number of Fatalities in Accidents Involving Buses and Tourist Buses and Their Share of Total Fatalities in the EU27 (2013–2023).

Source: European Commission, 2025

Figure 3. Results of Pre- and Post-Tests (I–V) for the Period 2023–2024.

Source: Zdravković, K. (2025)

areas (see Figure 3), based on data from the co-author's research (Zdravković, 2025). The greatest progress was observed among drivers with higher levels of education and longer work experience, particularly in the field of international transport. A difference was also noted in favor of those who completed basic training compared to drivers with recognized rights, indicating a greater effect of formalized education.

The testing covered the following areas:

I. Current regulations in the field of freight and passenger transport – **636 drivers tested**
II. Basic regulations on drivers' hours of service, rest periods, and use of tachographs – **580 drivers tested**
III. Current issues in using tachograph devices, malfunctions, and penalties for violations – **1,163 drivers tested**
IV. Proper vehicle operation, loading/unloading of cargo in accordance with safety requirements – **1,015 drivers tested**
V. Transport-related documentation – **799 drivers tested**

The best results were achieved in the areas of driving hours and tachograph usage (68%), as well as in regulations related to transport and loading/unloading procedures (64%). The weakest results (32%) were observed in the practical application of tachographs and error identification, indicating the need to improve the

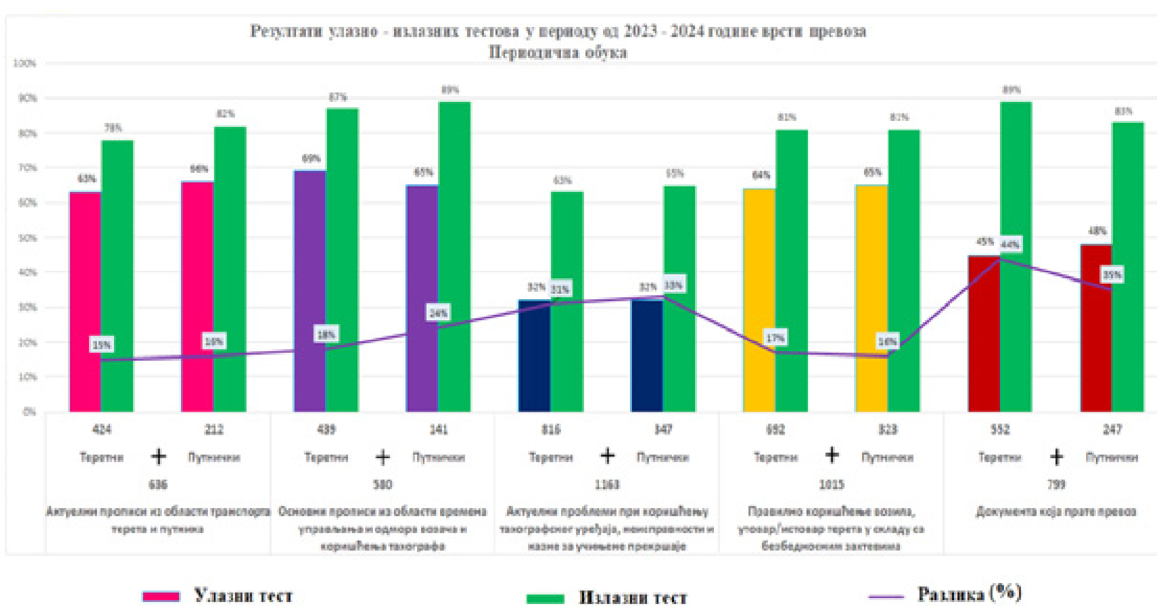

Figure 4. Results of Pre- and Post-Tests (I–V) for the Period 2023–2024, Showing Drivers Qualified for Freight and Passenger Transport.

Source: Zdravković, K. (2025)

content and methodology of training in this segment. Analysis of pre and post test results showed that the largest difference (41%) occurred in the area of transport-related documentation, highlighting the high effectiveness of the training process in this segment.

According to Figure 4, overall pre and post test results did not show statistically significant differences between freight and passenger transport drivers; however, specific differences were noted in thematic areas. The most pronounced difference was observed in the documentation segment, where passenger transport drivers had slightly better initial results (48%) compared to freight transport drivers (45%),which is associated with more frequendocumentation checks in public and international passenger transport.

However, freight transport drivers showed greater progress during the training, achieving a final score of 89% compared to 83% for passenger transport drivers. The difference between pre- and post-test results was 44% for freight transport and 35% for passenger transport, confirming the high effectiveness of the training for freight drivers, particularly in activating previously acquired practical knowledge (e.g., waybills, customs documentation).

In the area of regulations on driving hours and tachograph use, freight transport drivers had slightly better initial results (69% vs. 65%), which can be explained by stricter controls in international transport. However, passenger transport drivers demonstrated greater progress after training (24% vs. 18%), finishing with an average score of 89% compared to 87% for freight drivers.

These results indicate that the work environment significantly influences training outcomes, particularly in public passenger transport, where safety and compliance with regulations are directly linked to service quality.

Based on the analysis of pre- and post-test results and outcomes achieved during the seminars of periodic training for professional drivers, an evaluation of the quality of the training process and instructor performance was conducted. Instructor ratings, provided by participants at the end of the training (on a scale of 1 to 5, where "1" indicates complete dissatisfaction and "5" complete satisfaction), are presented in Figure 5.

The results show that instructors received exceptionally high average ratings, regardless of participants' initial knowledge level and achieved outcomes. For seminars with the lowest pre- and post-test results (Seminar III – Current Issues in Tachograph Usage), the average rating was 4.85, while for seminars with the highest progress (Seminar V – Transport-Related Documentation), the average rating was 4.95.

These findings indicate that participants' perception of the quality of the training process is not directly linked to objective test results; rather, participants generally rate instructors highly, even in cases where knowledge outcomes were relatively modest.

Analysis of evaluation data from Figures 6 and 7 shows a consistently high level of participant satisfaction across all parameters. The only notable difference was observed in the segment related to the novelty of training content: in response to the question, "The material we studied was new to me," Seminar III received an average rating of 4.58, while Seminar V received 4.73. This suggests that participants in Seminar III were somewhat more familiar with the training topics prior to attending, which may have influenced the slightly lower effectiveness in acquiring new knowledge.

Overall results indicate that the high level of instructor satisfaction (average above 4.8) reflects the good acceptance of the training process, regardless of the actual test results. This demonstrates the instructors' strong pedagogical skills and their ability to adapt the training to participants' needs.However, a mismatch was observed between subjective perception and objective results in seminars with lower test scores, where instructors still received very high ratings. This suggests that participant evaluations do not always provide a reliable indicator of the actual level of knowledge acquired.Therefore, it

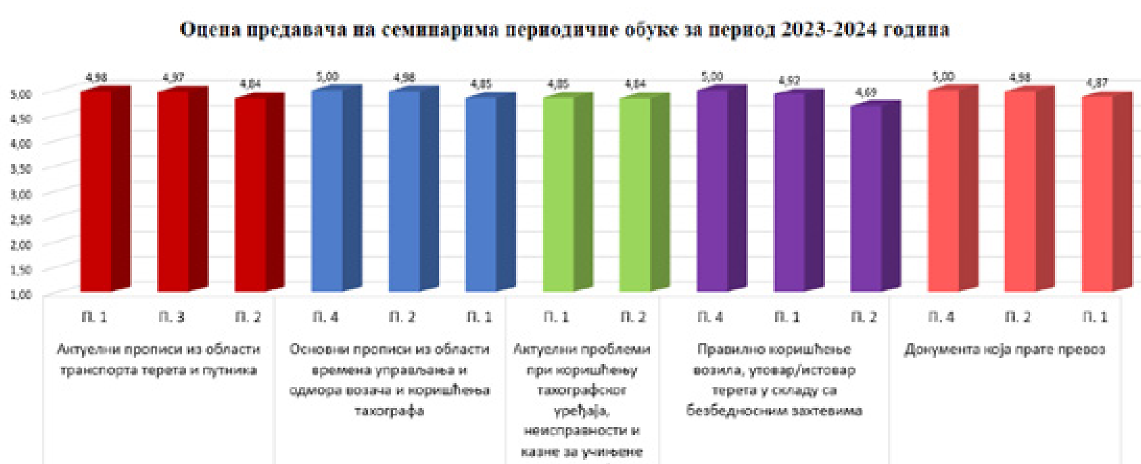

Figure 5. Instructor Ratings at Periodic Training Seminars for the Period 2023–2024.

Source: Zdravković, K. (2025)

Figure 6. Evaluation of the Periodic Training Seminar on: Current Issues in Tachograph Usage, Malfunctions, and Penalties for Violations.

Source: Zdravković, K. (2025)

is recommended to use combined criteria, i.e., applying knowledge tests alongside participant evaluations, in order to obtain a more complete picture of the effectiveness of the training process.

It is particularly important to note the influence of prior knowledge on the evaluation of training, where ratings for **new material** were slightly lower (4.58) in Seminar III. This confirms that participants with greater prior knowledge tend to evaluate the training more critically and generally show smaller improvements in post-test results (31% for freight drivers and 33% for passenger drivers), compared to Seminar V, where the rating for **new material** was 4.73, and the difference in pre and post test scores was 44% for freight drivers and 33% for passenger drivers.

The practical implications of these findings indicate the need to introduce more diverse teaching methods and to adapt content to different groups of participants according to their level of prior knowledge. Such an approach can establish a better balance between subjective evaluations and objective results, while regular analysis of evaluation and testing data allows for continuous improvement of the training process and targeted focus on areas with the greatest gap between perception and actual knowledge gains.

Regarding the implementation of basic and additional training conducted by authorized training centers, followed by professional examinations and analysis of available data by the Traffic Safety Agency, indicators of achieved training quality were obtained. These indicators are based on projected quality requirements, specifically the criteria for passing the theoretical part of the professional examination (Table 2).

According to the applicable criteria, in order for a driver to successfully pass the professional exam, it is necessary to achieve at least 75% of the total number of points (that is, 75 out of 100 points).Within the scope of this seminar paper, the period from 15 June 2020, when

Figure 7. Evaluation of the Periodic Training Seminar on: Transport-Related Documentation.

Source: Zdravković, K. (2025)

Table 2. Number of Drivers in Basic and Additional Training and Examinations in the Republic of Serbia

Year	Number of Drivers who completed 140-hour training – Freight		Number of Drivers who completed 35-hour training–Passenger	
	Attended the Examination	Passed the Examination	Attended the Examination	Passed the Examination
Year 2020	88	81 (92%)	96	85 (88%)
Year 2021	264	206 (78%)	250	194 (78%)
Year 2022	321	279 (87%)	239	194 (81%)
Year 2023	514	452 (88%)	301	244 (81%)
Year 2024	1.093	914 (84%)	413	333 (81%)
Total	2.280	1.932 (85%)	1.299	1.050 (81%)

Source: Zdravković, K. (2025)

the Serbian Road Safety Agency began implementing the training and examination program, until 15 December 2024 was analyzed. This timeframe represents the period for which relevant ABS data on conducted training programs and examinations were available.The results achieved during the observed period confirmed the projected quality of the training system, given that the pass rate was defined in accordance with the requirements and structure of the professional exam. Specifically, a high percentage of successfully passed exams was recorded:

- for the **basic accelerated training program** of 140 instructional hours, a total of 2,280 drivers took the exam, of whom 1,932 passed successfully, resulting in **a pass rate of 85%.**
- For the **additional training program** of 35 instructional hours, 1,299 drivers took the exam, and 1,050 passed, which corresponds to a **pass rate of 81%.**

Following the amendments to the legal framework and the abolishment of mandatory training (March 2025), the Serbian Road Traffic Safety Agency continued to administer professional examinations for drivers who had completed the initial or periodic qualification training. In the period January–May 2025, the results were as follows:

- After completing the **140-hour training for the transport of goods**, 648 drivers took the exam, 503 of whom passed, resulting in a **78% pass rate**.
- After completing the **35-hour training for the transport of passengers**, 130 drivers took the exam, 106 of whom passed, which corresponds to **a pass rate of 81%.**

When compared to the results from the previous period (2020–2024), a **slight decrease in the pass rate** can be observed among drivers obtaining the qualification for goods transport (from 85% down to 78%), while the success rate among drivers qualifying for passenger transport remained stable at approximately 81% (Table 3).

Following the adoption of legislative amendments, according to which attending training was no longer mandatory for individuals over 21 years of age (for goods transport) and 24 years of age (for passenger transport), the Road Traffic Safety Agency organized exams for this category of drivers.

In the period from May to September 2025, the results showed a significant decline in the pass rate compared to previous periods in which the trainings were mandatory.

For the **initial qualification for freight transport**, 390 drivers took the exam, of whom 177 passed successfully, which represents only **45% pass rate**. This result indicates a drastic decline in success compared to previous periods, when the pass rate exceeded 75%.On the other hand, only one candidate took the exam for acquiring the **additional qualification for freight transport** during this period, and the candidate passed successfully. However, due to the extremely small sample size, this result is not statistically relevant and was not considered in further analysis (Table 4).

In addition to the freight transport exams, during the same period, exams were also conducted for obtaining initial and additional qualifications for passenger transport.

For the initial qualification in passenger transport, 139 drivers took the exam, of which 79 passed successfully, representing a pass rate of 57%.

Table 3. Number of Drivers in Basic and Additional Training and Examination Procedures in the Republic of Serbia

Year	Number of Drivers who completed 140-hour training – Freight		Number of Drivers who completed 35-hour training–Passenger	
	Attended the Examination	Passed the Examination	Attended the Examination	Passed the Examination
01.01-21.05.2025.	648	503 (78%)	130	106 (81%)
Total	648	503 (78%)	130	106 (81%)

Source: Zdravković, K. (2025)

Table 4. Number of drivers taking qualification exams for Freight Transport in the Republic of Serbia

Year	Number of drivers taking the exam for the initial qualification – freight transport		Number of drivers taking the exam for the additional qualification – freight transport	
	Attended the Examination	Passed the Examination	Attended the Examination	Passed the Examination
22.05-12.09.2025.	390	177 (45%)	1	1 (100%)
Total	390	177 (45%)	1	1 (100%)

Source: Zdravković, K. (2025)

Table 5. Number of drivers taking exams for obtaining passenger transport qualifications in the Republic of Serbia

Year	Number of drivers taking the initial qualification exam – passenger transport		Number of drivers taking the additional qualification exam – passenger transport	
	Attended the Examination	Passed the Examination	Attended the Examination	Passed the Examination
22.05-12.09.2025.	139	79 (57%)	54	33 (61%)
Total	139	79 (57%)	54	33 (61%)

Source: Zdravković, K. (2025)

For the additional qualification in passenger transport, 54 drivers took the exam, of which 33 passed successfully, representing a pass rate of 61% (Table 5).

DISCUSSION

The research results, together with the analysis of the regulatory framework, statistical indicators, and the evaluation of professional driver training in the Republic of Serbia, highlight several important findings relevant to improving road traffic safety and the training system.

Impact of alignment with European Standards

The national system for training professional drivers in Serbia is largely aligned with Directive 2003/59/EC, which regulates initial, accelerated, and periodic training. This alignment has contributed to a gradual improvement in drivers' competencies and a reduction in traffic accidents. However, compared to EU countries, progress in Serbia remains slower. Although commercial vehicles account for about 26% of traffic accidents, they are responsible for a disproportionately higher share of fatal outcomes (27%), emphasizing the need for continuous education and the protection of vulnerable road users.

Effectiveness of the training process and the role of Instructors

Analysis of the entry–exit tests confirms that periodic training significantly increases drivers' knowledge, particularly in areas such as documentation and tachograph usage. Differences between freight and passenger transport drivers indicate that the work environment and prior knowledge significantly influence learning effectiveness. Instructor evaluations (average ratings above 4.8) confirm high pedagogical quality, yet a mismatch between subjective evaluation and actual test results was observed. This highlights the need for a combined assessment approach, integrating objective tests with participant evaluations to obtain a more complete picture of training effectiveness.

Consequences of removing mandatory training

Amendments in 2025, which removed mandatory training for drivers over 21 (freight) and 24 years (passenger), led to a sharp decline in exam pass rates: from 85% to 45% for freight drivers and from 81% to 61% for passenger drivers. These data clearly indicate that mandatory training is a key factor in maintaining professional competencies and road safety. Eliminating regular education reduces knowledge standardization, quality control, and increases accident risk.

European directives, particularly 2022/2561/EC, emphasize the importance of digitalization of training, flexible learning methods, assessment of psychophysical abilities, and continuous professional development of instructors. Based on the comparative analysis, the following recommendations are suggested:

1. Reinstatement of Mandatory Training for All Categories of Professional Drivers
2. Establishment of an Integrated Training Model that enables drivers of freight vehicles and buses to acquire the appropriate qualifications through a unified training process.
3. Introduction of a Risk Perception Test for all commercial vehicle drivers.
4. Stepwise Acquisition of Professional Driving Licenses under the supervision of experienced drivers.
5. Integration of Digital Teaching Tools and Simulators to enhance the practical effectiveness of training.
6. Continuous Monitoring and Analysis of Test Results in combination with subjective trainee evaluations.
7. Professional Development of Instructors through regular training and certification programs.

8. Application of EU Standards for Driver Assessment and Certification to reduce accident rates and improve road safety.
9. Strengthening the Capacity of State Institutions for more effective oversight of training centers.
10. Introduction of a Co-Financing Model for Initial Training involving candidates, employers, and local authorities.

Concluding remarks

Overall, these conclusions and recommendations indicate that improving the professional driver training system is a prerequisite for developing competent, responsible, and safe drivers. The integration of digital technologies, continuous monitoring of knowledge, and the professional development of instructors will enable long-term enhancement of traffic safety culture and a reduction in road accidents in Serbia, in line with European standards and the "Vision Zero" concept.

CONCLUSION

The research confirms that systematic and standardized training plays a decisive role in developing professional driver competencies and improving road traffic safety.

Based on the conducted study, the authors have identified several key findings that illustrate the main conclusions and recommendations regarding the topic:

1. Serbia has largely aligned its system with Directive 2003/59/EC, but further approximation to European practices is needed.
2. Periodic training significantly improves knowledge and operational skills, particularly in the areas of documentation and tachograph use.
3. The abolition of mandatory training in 2025 led to a decline in pass rates and a reduction in knowledge quality, confirming the necessity of compulsory training.
4. There is a need to introduce digital learning methods, driving simulators, and continuous professional development for instructors.
5. Continuous analysis of testing results and participant evaluations is essential for monitoring training quality and effectiveness.
6. An integrated system of training and examinations for obtaining professional driver licenses and initial qualifications should be established.
7. A subsidized financial model should be implemented to ensure the sustainability and accessibility of training for young drivers aiming to achieve professional status.

Overall, the development of an integrated and standardized training system, aligned with European directives, provides the foundation for building a safe, professional, and sustainable transport system in the Republic of Serbia, taking into account the best practices in neighboring countries and the EU2

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PRELIMINARY REPORT

Development of road traffic safety in the republic of Serbia from 2014 to 2024

Filip Živković
Master inženjer saobraćaja, Saobraćajni Fakultet, Beograd, Republika Srbija, f_zivkovic@outlook.com

Boris Antić
Prof. dr, doktor saobraćajnih nauka, Saobraćajni Fakultet, Beograd, Republika Srbija, b.antic@sf.bg.ac.rs

Danislav Drašković
Prof. dr, Panevropski univerzitet Apeiron, Banja Luka, Republika Srpska, Bosna i Hercegovina, danislav.m.draskovic@apeiron-edu.eu

Tomislav Petrović
Diplomirani inženjer saobraćaja, tomicakg@gmail.com

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Abstract: The paper analyzes the development of road traffic safety in the Republic of Serbia from 2014 to 2024, aiming to determine the progress achieved in reducing traffic accident consequences and improving institutional management in this field. The research is based on data from the Statistical Office of the Republic of Serbia, the Ministry of Interior, and local road safety strategies, using descriptive–comparative and indicator analyses. The total number of fatalities decreased by 7%, while the number of injured persons increased by 8%, indicating partial effectiveness of implemented measures and the need for further improvement. A population decrease of more than 7% led to a 12% increase in public risk, whereas a 32% rise in the number of registered vehicles resulted in a 22% reduction in traffic risk. The highest increase in mortality was recorded among children, while the most severe consequences occurred on roads outside urban areas. At the same time, the number of local road safety strategies increased from one in 2014 to 96 in 2024, representing significant institutional progress. The results confirm the necessity of an integrated approach combining infrastructural, educational, and technological measures, as well as the application of analytical methods such as benchmarking and Data Envelopment Analysis (DEA) in the planning process. Achieving the "Vision Zero" goal requires consistent monitoring of performance indicators and cooperation across all levels of governance to ensure long-term improvement of road traffic safety in the Republic of Serbia.

Key words: Road traffic safety; risk analysis; safety strategies; benchmarking; Data Envelopment Analysis (DEA).

INTRODUCTION

Road traffic safety represents one of the key challenges of sustainable development and public health in contemporary society. Despite continuous efforts by international organizations and national governments, road traffic crashes remain among the leading causes of death and injury worldwide, with more than 1.35 million fatalities annually, according to the World Health Organization. This situation highlights the need for systematic and scientifically grounded approaches that enable a detailed assessment of road traffic safety performance and the identification of factors that significantly contribute to risk. It is important to emphasize that road traffic crashes do not only result in loss of life and disability, but also lead to unemployment, financial hardship, and psychological trauma that have long-term consequences for the families of victims (Másilková, 2017). Health professionals consistently recognize road traffic injuries as one of the leading public health issues - a "silent epidemic" - yet this problem remains insufficiently acknowledged at the level of national policy (Fanai & Mohammadnezhad, 2023).

Road traffic safety today is no longer viewed solely as an engineering challenge, but as an integral component of social and economic sustainability. In other words, road traffic safety represents one of the key issues of contemporary society, as it lies at the intersection of technological progress, social transformation, and human behaviour within a dynamic environment (Stipdonk et al., 2012). Modern research trends increasingly shift the focus away from traditional approaches that examine road traffic crashes in isolation, toward integrated frameworks that incorporate infrastructure, road user behaviour, institutional capacity, public health, and economic impacts. This paradigm shift has contributed to the development of interdisciplinary models that connect different levels of the system - from technical and managerial to political and societal.

One of the most influential concepts shaping contemporary road traffic safety research is benchmarking - a systematic process of comparing performance across countries, regions, and local jurisdictions in order to identify best practices in road traffic safety management. Wegman and Oppe (2010), through the SUNflower model, emphasized the importance of linking Safety Performance Indicators (SPIs) with policy frameworks and institutional factors. This model enabled a deeper understanding of the interdependencies between political governance, infrastructural characteristics, and actual road traffic outcomes. Utilizing data from multiple EU Member States, the authors demonstrated a strong correlation between the maturity of institutional systems and road traffic safety performance. Countries with stable institutional structures, long-term strategies, and independent research institutes consistently achieve the best results. Wegman and Oppe highlight that the development of evidence-based policy is essential for the sustainable reduction of road traffic fatalities and injuries.

Shen et al. (2020) prepared a study with the aim of developing an integrated model that links road traffic safety performance, institutional capacity, and the effectiveness of policy implementation. The authors argue that benchmarking should not be limited to a quantitative comparison of indicators (e.g., fatalities per capita), but should instead represent a learning process based on comparing systems, policies, and institutional structures. Shen et al. developed a Multi-Layer Data Envelopment Analysis (DEA) model that enables integrated performance assessment across three levels: the Operational level (measuring the efficiency of specific interventions), the Tactical level (evaluating the effectiveness of implementing national strategies and action plans), and the Strategic level (analyzing institutional maturity and the quality of road traffic safety management). Countries such as Sweden, the United Kingdom, the Netherlands, and Norway achieved the highest efficiency values across all levels, while Bulgaria, Romania, and Latvia ranked among the least efficient. The study particularly emphasizes that middle-income countries, although often making progress in certain areas (e.g., infrastructure), tend to lag behind in institutional coordination and policy implementation.

The study prepared by Pinna et al. (2024) presents an integrated approach to analyzing road traffic safety in urban environments, aligned with the European Union's objectives of halving the number of road traffic fatalities by 2030 and achieving "vision zero" by 2050. The authors developed a method based on Geographic Information Systems (GIS) that enables a multi-layered assessment of road traffic safety, taking into account not only the locations of road traffic crashes but also factors such as traffic flow, pavement condition, and the presence of attraction points such as schools, hospitals, and commercial areas. The methodology is grounded in the superposition of four georeferenced data layers: crash locations, traffic flows, pavement conditions, and attraction points. Each layer contains a distinct set of information, and their integration enables a comprehensive spatial analysis of road traffic safety patterns. All data are collected and integrated within a GIS environment, allowing for the overlay and examination of interrelationships among variables. The results indicate that 71% of saturated road segments experience at least two or more crashes, while 72% of crashes occur on segments with poor or very poor pavement conditions.

Christoforou et al. (2012) investigate the potential for integrating real-time road traffic data into road traffic safety analysis. The primary goal of the study is to develop a method that links variations in traffic flow and volume to the occurrence of road traffic crashes, thereby enabling dynamic risk assessment and proactive road traffic management. The authors emphasize that traditional road traffic safety analysis methods predominantly rely on historical crash data, which are static and limited in scope, whereas real-time data allow for a dynamic evaluation of risk. The study highlights that advancements in information and communication technologies - such as sensors, GPS systems, and Intelligent Transportation Systems (ITS) - provide opportunities for continuous collection and analysis of variables such as speed, volume, and travel time. These data can be used to detect "critical situations." By applying a 15-minute time period (loop detector) before and after each crash, the researchers identified changes in key traffic variables - volume, speed, and flow - and thus detected patterns that precede road traffic crashes. The findings show that most crashes are preceded by periods of increased instability in traffic flow. Specifically, a substantial decrease in average speed and an increase in speed variance typically occur within 5 to 10 minutes prior to a crash. These changes are particularly pronounced in high-volume traffic zones, where drivers are required to brake and accelerate frequently.

This study is based on an analysis of data collected from various sources, with the aim of determining the degree of reliability, comparability, and applicability of information in assessing the state and development of road traffic safety in 2024 relative to 2014. The core methodological principle employed is a multi-layered approach, which involves the use of primary, secondary, and tertiary data sources. Primary sources include official statistical databases and reports issued by competent institutions. Secondary sources encompass relevant scientific and professional publications, as well as data obtained from international databases, while tertiary sources consist of local road traffic safety strategies, official gazettes, and the official websites of local self-government units.

DEMOGRAPHIC CHARACTERISTICS

In the Republic of Serbia, population censuses are conducted periodically (the two most recent censuses were carried out in 2011 and 2022). In this study, census data are used as a source of information on the total population and projected population figures, which serve as the basis for calculating public exposure to road traffic risk. In addition, the Statistical Office of the Republic of Serbia (RZS) annually publishes the Statistical Yearbook, which is used in this study as a source of information on the number of registered vehicles, enabling the calculation of vehicle-based exposure to road traffic risk.

Population Size

According to the 2011 Population Census in the Republic of Serbia, the country had 7,186,862 inhabitants, while the 2022 Census recorded 6,647,003 inhabitants. Based on annual population estimates (derived from the previously conducted census, natural population change, and internal migration), it is possible to obtain approximate population figures for 2014 and 2024 - the two reference years used to evaluate the development of road traffic safety in the Republic of Serbia. It is estimated that Republic of Serbia had 7,131,787 inhabitants in 2014 and 6,623,183 inhabitants in 2024. When comparing only these two reference years, the population of the Republic of Serbia decreased by 508,604 inhabitants, or −7.13%.

Number of Registered Vehicles

According to the annual reports of the Statistical Office of the Republic of Serbia (SORS), data on the number of registered vehicles are available both at the national level and for each local self-government unit individually. The data show that in 2014 a total of 2,067,547 vehicles were registered (including 1,797,427 passenger cars), while in 2024 the number of registered vehicles increased to 2,792,489 (of which 2,389,105 were passenger cars). It is important to note that the total count includes motorcycles, mopeds, passenger cars, buses, freight vehicles, and work vehicles, whereas trailers were not considered in the analysis. Based on these data, the number of registered vehicles increased by 724,935, representing a growth of +32.16%.

The motorization rate in 2014 was 289.9 vehicles per 1,000 inhabitants, while in 2024 it increased to 421.6 vehicles per 1,000 inhabitants, representing a rise of approximately 45.4%. This increase indicates a significant growth in the level of motorization, meaning that the number of vehicles per inhabitant is considerably higher than a decade earlier. Although the population decreased by 7% between 2014 and 2024, the number of registered vehicles increased by 32%, which demonstrates a substantial rise in the motorization rate. This trend may be attributed to improved economic conditions, greater affordability and availability of vehicles, weakening public transport systems, and changes in lifestyle and demographic patterns. Higher motorization levels can lead to increased pressure on the road network, elevated crash risk, and greater strain on urban infrastructure. In other words, this trend may have negative effects on road traffic safety, the environment, and urban mobility - manifesting through higher congestion levels, increased pollution, and greater parking demand - which in turn influences the broader concept of urban road traffic safety.

ROAD TRAFFIC SAFETY ANALYSIS

Data on the number and consequences of road traffic crashes were collected using the Integrated Road Traffic Safety Database of the Road Traffic Safety Agency of the Republic of Serbia (RTSA). In the period from 2014 to 2024, a total of 376,847 road traffic crashes occurred, resulting in 5,986 fatalities and 215,269 injured persons. When comparing the research period, it is evident that the lowest number of crashes and their consequences occurred in 2020. However, due to the COVID-19 pandemic and the measures implemented to limit the spread of the virus, this year cannot be considered representative. According to the data presented in Table 2, a decrease in the total number of crashes, as well as crashes resulting only in material damage, was recorded in 2024 compared to 2014. This trend may indicate improvements in traffic control and regulation, as well as increased driver caution in lower-risk situations. However, at the same time, an increase in the number of crashes involving injured and fatally injured persons is observed, meaning that the number of crashes with casualties has risen. This phenomenon suggests that although the overall frequency of crashes is declining, the severity of their consequences for road users is increasing.

According to the data presented in Table 4, opposite trends are observed in the number of fatalities and injured persons in road traffic crashes in 2014 and 2024. The number of fatalities decreased by 7.83%, which represents a positive indicator in terms of reducing the most severe consequences of road traffic crashes. However, the total number of injured persons increased by 8.11%, and the total number of casualties (fatalities and injuries) increased by 7.75% compared to 2014. These data indicate that, although there has been a slight decline in the number of fatal outcomes, overall exposure to risk and the severity of crash consequences remain high, demonstrating the need for more intensive preventive measures and stronger control of road user behaviour.

Table 1. Road Traffic Crashes in the Period 2014–2024

Year	Fatal crashes	Injury crashes	Total casualties	Property-damage-only crashes	Total crashes
2014	476	12568	13044	21969	35013
2015	548	13109	13657	20518	34175
2016	551	13866	14417	21558	35975
2017	525	14226	14751	21715	36466
2018	491	13710	14201	21608	35809
2019	494	13748	14242	21525	35767
2020	459	11850	12309	18401	30710
2021	482	13271	13753	20821	34574
2022	505	12802	13307	19933	33240
2023	470	12993	13463	19385	32848
2024	481	13093	13574	18696	32270

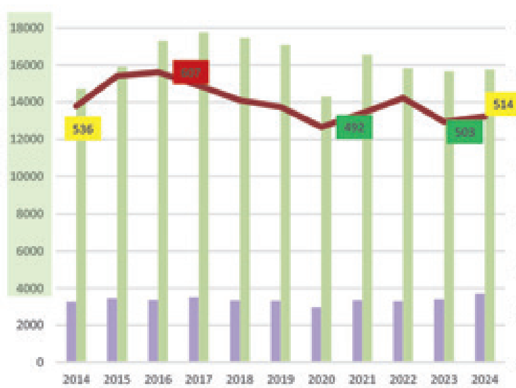

Figure 1. Road Traffic Crashes in the Period 2014–2024.

These results indicate that the road traffic safety management system in the Republic of Serbia, despite notable institutional improvements following the adoption of the Law on Road Traffic Safety and the implementation of national strategies, has not yet reached a sufficient level of effectiveness in reducing the risk of road traffic casualties. The increase in the number of injured persons may be attributed to the growing number of vehicles in traffic, higher exposure levels in urban environments, as well as the limited implementation of local road traffic safety strategies. This is particularly evident in towns and rural areas, where infrastructure development and the enforcement of safety measures lag behind the national average.

Further analysis should examine the influence of factors such as traffic density, vehicle age, the use of seat belts and protective helmets, as well as the implementation of safety measures in school zones and on local roads. Particular attention should be directed toward the so-called weighted risk indicators - public risk and traffic risk - as they provide a more objective representation of the population's actual exposure to road traffic hazards, taking into account demographic changes and shifts in motorization levels throughout the analyzed period.

Table 2. Comparison of the number of road traffic crashes between 2014 and 2024.

Year	Fatal crashes	Injury crashes	Total casualties	Property-damage-only crashes	Total crashes
2014	476	12568	13044	21969	35013
2024	481	13093	13574	18696	32270
Difference	5	525	530	-3273	-2743
Percentage Difference	1.05%	4.18%	4.06%	-14.90%	-7.83%

Table 3. Consequences of Road Traffic Crashes in the Period 2014–2024.

Year	Fatalities	Severe Injuries	Slight Injuries	Injured Persons	Total Injured
2014	536	3275	14720	17995	18531
2015	599	3448	15903	19351	19950
2016	607	3362	17304	20666	21273
2017	579	3503	17765	21268	21847
2018	548	3336	17452	20788	21336
2019	534	3322	17094	20416	20950
2020	492	2954	14297	17251	17743
2021	521	3347	16557	19904	20425
2022	553	3302	15817	19119	19672
2023	503	3397	15660	19057	19560
2024	514	3715	15739	19454	19968

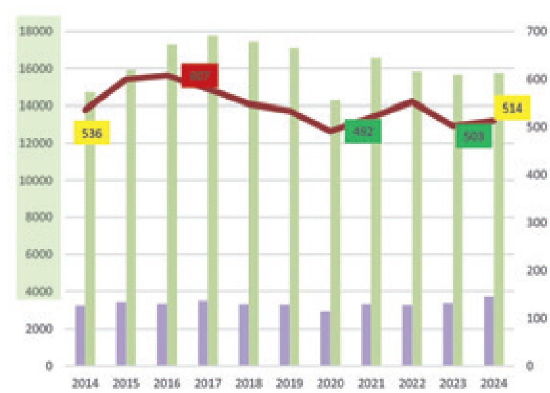

Figure 2. Consequences of Road Traffic Crashes in the Period 2014–2024.

Table 4. Comparison of Road Traffic Crash Consequences Between 2014 and 2024.

Year	Fatalities	Severe Injuries	Slight Injuries	Injured Persons	Total Injured
2014	536	3275	14720	17995	18531
2024	514	3715	15739	19454	19968
Difference	-22	440	1019	1459	1437
Percentage Difference	-7.83%	13.44%	6.92%	8.11%	7.75%

Road Traffic Safety Analysis by Age Groups

The analysis of road traffic safety by age groups for the period 2014-2024 reveals distinct trends in the number of fatalities, injuries, and overall casualties. In the 0-14 age group, a 60% increase in the number of fatalities was recorded, along with a slight rise in the number of slightly injured and total casualties. This indicates a growing exposure to risk among the youngest road users. Such a trend may be the result of insufficient protection measures in school zones and residential areas, as well as inadequate education of children regarding safe behaviour in road traffic.

In the 15-30 age group, the number of fatalities decreased by 13.53%, yet the number of injured and total casualties increased. This suggests that despite the reduction in fatal outcomes, young people remain one of the most vulnerable categories of road users. Their elevated risk is most commonly associated with limited driving experience, a propensity for speeding, and various forms of risky behaviour. Among the key factors contributing to increased risk in this age group are excessive speed, mobile phone use while driving, and non-compliance with speed limits or right-of-way rules.

In the 31-65 age group, a decrease in the number of fatalities is observed, accompanied by an increase in the number of injured persons and total casualties. Since this group represents the largest share of the active population and participates most frequently in traffic, the rise in the number of injured persons may be attributed to more intensive vehicle use, higher volumes of daily commuting, and increased exposure to urban road traffic congestion. Despite this, the stabilisation of the number of fatalities in this age group may be partially attributed to advancements in passive road safety systems.

In the population aged 65 and above, an increase in the number of fatalities and seriously injured persons is evident, while the total number of casualties shows a slight decrease. These results indicate that older road users are more susceptible to severe outcomes due to physical vulnerability and slower reaction times, which highlights the need for implementing measures aimed at improving infrastructure and ensuring safer mobility for elderly pedestrians and drivers. Furthermore, it is essential to develop systematic programmes for assessing the physical and cognitive abilities of older drivers, as well as improving lighting and traffic signalling in areas they use most frequently.

Overall, the data across age groups confirm that road traffic risk in the Republic of Serbia has not decreased uniformly among all segments of the population. While moderate progress can be observed among the working-age adult population, the youngest and oldest groups have experienced an increase in the severity of crash outcomes. This pattern highlights the need for targeted road traffic safety policies - particularly those focused on protecting children in school zones, educating young drivers, and improving mobility conditions for older adults. Such measures are aligned with the Road Traffic Safety Strategy of the Republic of Serbia, which identifies the reduction of casualties among vulnerable road users and the promotion of equity in access to a safe road traffic environment as key priorities.

Table 5. Comparison of Road Traffic Crash Consequence Indicators by Age Groups for 2014 and 2024.

Analysis of Road Safety for the 0–14 Age Group					
Year	Fatalities	Severe Injuries	Slight Injuries	Injured Persons	Total Injured
2014	10	215	1264	1479	1489
2024	16	196	1328	1524	1540
Difference	6	-19	64	45	51
Percentage Difference	60%	-8.84%	5.06%	3.04%	3.43%
Analysis of Road Safety for the 15–30 Age Group					
Year	Fatalities	Severe Injuries	Slight Injuries	Injured Persons	Total Injured
2014	133	812	4938	5750	5883
2024	115	876	5146	6022	6137
Difference	-18	64	208	272	254
Percentage Difference	-13.53%	7.88%	4.21%	4.73%	4.32%
Analysis of Road Safety for the 31–65 Age Group					
Year	Fatalities	Severe Injuries	Slight Injuries	Injured Persons	Total Injured
2014	270	1711	7342	9053	9323
2024	237	1850	7723	9573	9810
Difference	-33	139	381	520	487
Percentage Difference	-12.22%	8.12%	5.19%	5.74%	5.22%
Analysis of Road Safety for the over 65 Age Group					
Year	Fatalities	Severe Injuries	Slight Injuries	Injured Persons	Total Injured
2014	123	740	1628	2368	2539
2024	146	793	1542	2335	2481
Difference	23	53	-86	-33	-58
Percentage Difference	18.70%	7.16%	-5.28%	-1.39%	-2.28%

Road Traffic Safety Analysis by Road User Category

During 2014 and 2024, different trends were recorded in the consequences of road traffic crashes depending on the category of road users - drivers, pedestrians, and passengers. The analysis of the number of fatalities, seriously and slightly injured persons, as well as the total number of casualties, provides a detailed insight into the dynamics of risk and crash outcomes, and enables the identification of potentially high-risk groups.

Among drivers, a significant increase in all categories of crash consequences has been observed. These data indicate a rise in risk and severity of outcomes for drivers, which may be associated with the growing number of vehicles, higher traffic intensity, and increasingly complex traffic flows. The increase in serious injuries relative to the number of fatalities particularly highlights potential shortcomings in compliance with traffic regulations, the insufficient use of safety systems, or the effectiveness of preventive measures. Additionally, the increasing use of mobile phones while driving, driver fatigue, and the influence of psychoactive substances should be noted, as these factors substantially elevate the likelihood of crashes with severe consequences. In contrast, pedestrians recorded a decline in almost all indicators. This trend suggests a positive impact of preventive measures and infrastructural solutions, such as pedestrian crossings, improved signalling, traffic-calming devices, and road user education. The slightly smaller reduction in the number of seriously injured pedestrians compared to fatalities may be attributed to improved medical intervention and faster emergency response times. However, continued systematic improvements in pedestrian safety remain necessary, particularly in school zones and densely populated urban areas, where pedestrians continue to represent one of the most vulnerable road user categories.

Among passengers, the number of fatalities decreased, while the number of injured persons increased. These results indicate the effectiveness of in-vehicle safety systems - such as seat belts and airbags - which help reduce mortality but do not fully eliminate injuries in the event of a crash. It is particularly important to highlight the passenger category within the 0-14 age group. Among child passengers, the number of fatalities increased significantly, from 4 to 16 (a 300% increase), accompanied by a rise in the number of injured and total casualties. These data point to a substantial increase in risk for children as passengers, which may be attributed to the higher number of transport modes used, non-compliance with proper child restraint systems, or insufficient enforcement of safety measures within vehicles. This category requires special attention in designing preventive strategies and ensuring strict adherence to child transportation regulations.

The analysis by road user category shows that progress in road traffic safety in the Republic of Serbia is not occurring uniformly. While pedestrians and passengers are, to some extent, better protected, the risk for drivers and child passengers is increasing significantly. These results highlight the need for targeted measures within the Road Traffic Safety Strategy of the Republic of Serbia, particularly in the areas of driver behaviour control, the use of safety systems, and the protection of children as passengers. At the same time, the findings suggest that the existing monitoring and evaluation system requires further improvement through better integration of data related to crash causes, demographic characteristics, and the spatial distribution of crashes. Such an approach would enable more precise, data-driven decision-making aimed at reducing casualties among the most vulnerable categories of road users.

Table 6. Comparison of Road Traffic Crash Consequence Indicators by Participant Type for 2014 and 2024.

Year	Participant Type	Fatalities	Severe Injuries	Slight Injuries	Injured Persons	Total Injured
2014	DRIVER	281	1663	7459	9122	9403
2024	DRIVER	308	2031	8457	10488	10796
Difference		27	368	998	1366	1393
Percentage Difference		9.61%	22.13%	13.38%	14.97%	14.81%
Year	Participant Type	Fatalities	Severe Injuries	Slight Injuries	Injured Persons	Total Injured
2014	PEDESTRIAN	128	825	2002	2827	2955
2024	PEDESTRIAN	111	803	1794	2597	2708
Difference		-17	-22	-208	-230	-247
Percentage Difference		-13.28%	-2.67%	-10.39%	-8.14%	-8.36%
Year	Participant Type	Fatalities	Severe Injuries	Slight Injuries	Injured Persons	Total Injured
2014	PASSENGER	127	785	5247	6032	6159
2024	PASSENGER	95	872	5465	6337	6432
Difference		-32	87	218	305	273
Percentage Difference		-25.20%	11.08%	4.15%	5.06%	4.43%

Table 7. Comparison of Road Traffic Crash Indicators by Participant Type for the 0–14 Age Group in 2014 and 2024.

Year	Participant Type	Fatalities	Severe Injuries	Slight Injuries	Injured Persons	Total Injured
2014	DRIVER	1	56	133	189	190
2024	DRIVER	0	44	155	199	199
Difference		-1	-12	22	10	9
Percentage Difference		-100%	-21.43%	16.54%	5.29%	4.74%
Year	Participant Type	Fatalities	Severe Injuries	Slight Injuries	Injured Persons	Total Injured
2014	PEDESTRIAN	5	101	456	557	562
2024	PEDESTRIAN	0	75	311	386	386
Difference		-5	-26	-145	-171	-176
Percentage Difference		-100%	-25.74%	-31.80%	-30.70%	-31.32%
Year	Participant Type	Fatalities	Severe Injuries	Slight Injuries	Injured Persons	Total Injured
2014	PASSENGER	4	58	675	733	737
2024	PASSENGER	16	77	856	933	949
Difference		12	19	181	200	212
Percentage Difference		300%	30.76%	26.81%	27.29%	28.77%

Spatial Analysis of Road Traffic Safety

Data for 2014 and 2024 show a substantial increase in road traffic crashes and their consequences, with trends varying considerably depending on the location of occurrence - within settlements and outside settlements. In urban areas, an increase in all categories of crash outcomes has been recorded. These results indicate significant growth in the number of injury-related crashes in urban environments, which may be attributed to higher traffic density, more intensive movement of vehicles and pedestrians, and increasingly complex traffic flows in cities. Urban areas also face challenges such as limited parking capacity, insufficiently safe pedestrian and cycling infrastructure, and a growing number of vehicles on short-distance trips, all of which further increase the risk of interaction between different categories of road users.

In contrast, areas outside settlements recorded a far more dramatic increase across all indicators. These data point to substantially higher risk levels on rural and interurban roads, which may be associated with higher driving speeds, unfavourable road conditions, limited traffic control, and reduced accessibility of emergency medical services. Crashes outside settlements more frequently result in severe outcomes, making these areas critical points for infrastructure improvements and increased safety interventions. Insufficient protection along hazardous segments, lack of roadside barriers, poor night-time visibility, and inadequate pavement maintenance further intensify the severity of crash consequences on these roads.

The observed differences between crashes within and outside settlements highlight the need for a spatially differentiated approach to road traffic safety management. While urban areas require measures aimed at reducing interactions between motorized and non-motorized traffic (e.g., traffic-calming devices, 30 km/h zones, safe pedestrian crossings, cycling lanes), roads outside settlements require systemic interventions in infrastructure and speed management. In this context, recommendations from the European Safe System approach, as well as the Road Traffic Safety Strategy of the Republic of Serbia, emphasize the necessity of adapting safety management practices to the typology of space - urban, rural, and interurban.

Furthermore, it is essential to develop spatial risk indicators that combine crash frequency with demographic and traffic data (such as population density, number of vehicles, and road network length) to identify priority areas for intervention. This would enable the allocation of resources and measures to the highest-risk areas, in accordance with the principles of efficient and equitable road traffic safety management.

Table 8. Comparison of Road Traffic Crash Consequence Indicators Based on Spatial Analysis for 2014 and 2024.

Year	Urban Area	Fatalities	Severe Injuries	Slight Injuries	Injured Persons	Total Injured
2014	Urban Area	225	1569	7227	8796	9021
2024	Urban Area	237	2470	11407	13877	14114
Difference		12	901	4180	5081	5093
Percentage Difference		5.33%	57.43%	57.84%	57.76%	56.46%
Year	Urban Area	Fatalities	Severe Injuries	Slight Injuries	Injured Persons	Total Injured
2014	Non-Urban Area	95	377	1205	1582	1677
2024	Non-Urban Area	277	1245	4332	5577	5854
Difference		182	868	3127	3995	4177
Percentage Difference		191.58%	230.24%	259.50%	252.53%	249.08%

Table 9. Comparison of Road Traffic Crash Consequence Indicators According to Spatial Analysis for 2014 and 2024.

Year	Urban Area	Fatal crashes	Injury crashes	Total casualties	Property-damage-only crashes	Total crashes
2014	Urban Area	199	6343	6542	10581	17123
2024	Urban Area	231	10069	10300	15383	25683
Difference		32	3726	3758	4802	8560
Percentage Difference		16.08%	59.74%	57.44%	45.38%	49.99%
Year	Urban Area	Fatal crashes	Injury crashes	Total casualties	Property-damage-only crashes	Total crashes
2014	Non-Urban Area	90	901	991	1123	2114
2024	Non-Urban Area	250	3024	3274	3313	6587
Difference		160	2123	2283	2190	4473
Percentage Difference		177.78%	235.63%	230.37%	195.01%	211.59%

Risk Indicator Analysis

When comparing 2014 and 2024, significant changes can be observed in the structure and magnitude of road traffic crash consequences. The total number of fatalities decreased by 7.83%, which represents a positive trend in absolute terms, while the number of injured persons increased by 8.11%. These data indicate that although the number of fatal outcomes has slightly declined, the overall severity of road traffic casualties remains high, with a pronounced increase in the number of individuals sustaining serious bodily injuries.

When these changes are examined in relation to demographic indicators, a clearer picture emerges regarding the factors that influence overall risk levels. The decrease in the total population of the Republic of Serbia has resulted in an increase in the weighted public risk by +12.15% (the Public Risk Indicator – PRI was 154.7 casualties per 10,000 inhabitants in 2014, compared to 173.5 in 2024), since a smaller population is being compared with a similar or only slightly reduced number of casualties. This means that the individual risk per inhabitant has increased, indicating the need to evaluate road traffic safety not only through absolute numbers but also through relative indicators that more accurately reflect the population's true exposure to road traffic hazards.

On the other hand, the increase in the number of registered vehicles during the same period led to a reduction in the weighted traffic risk by −22.91% (the Traffic Risk Indicator – TRI was 533.8 casualties per 10,000 registered vehicles in 2014, compared to 411.5 in 2024). This reduction indicates that the rise in motorization has not been accompanied by a proportional increase in the number of crashes. Such a trend may be interpreted as a result of technological advancements in vehicles, stricter regulations, improved road maintenance, and more effective traffic enforcement. Moreover, the increasing adoption of active and passive vehicle safety systems contributes to mitigating the consequences of crashes.

It can be concluded that the weighted public and traffic risk indicators move in opposite directions, confirming the complexity of road traffic safety analysis. A decreasing population increases individual (public) risk, whereas a growing number of vehicles reduces the systemic (traffic) risk. These findings underscore the importance of a multidimensional approach to assessing and planning road traffic safety measures, particularly within the context of strategic management and the development of local and national programmes that must incorporate demographic, technological, and infrastructural factors.

These results confirm the need for road traffic safety evaluations to rely not only on absolute indicators of the number of casualties, but also on composite indicators that account for demographic changes, motorization levels, and economic activity. For this reason, the road traffic safety monitoring system should be oriented toward the introduction of performance indicators in line with European practices (EU Road Safety Performance Framework), in order to obtain a more realistic assessment of risk trends and to define intervention priorities more accurately in the forthcoming strategic period.

ROAD TRAFFIC SAFETY PERFORMANCE INDICATORS

Road Safety Performance Indicators (RSPI) represent measurable indicators that monitor key risk factors and the effects of road safety measures, such as the use of seat belts and helmets, speed, alcohol impairment, vehicle technical condition, and infrastructure quality. Their purpose is to enable the assessment, comparison, and improvement of road safety systems at both national and local levels by measuring the actual conditions that influence the occurrence of road traffic crashes.

In the Republic of Serbia, systematic measurement of these indicators began in 2013, in accordance with the guidelines of the European Commission and the ETSC, and is carried out by the Road Traffic Safety Agency of the Republic of Serbia in cooperation with the Ministry of Interior, the Statistical Office of the Republic of Serbia, and local road safety councils. This process forms the foundation for the development of analytically driven road safety management and for monitoring progress toward national strategic objectives.

Data on the average vehicle speed indicator for 2014 and 2024 show different trends depending on road type and vehicle category. Within settlements, a decrease in speed was recorded across all vehicle categories, most notably among passenger cars (−6.03%). This trend indicates a positive effect of speed-control measures, the installation of traffic-calming devices, enforcement cameras, and increased police supervision, as well as the gradual development of a safer driving culture in urban environments. On roads outside settlements, a slight reduction in speed was observed for most vehicle categories, with the exception of heavy goods vehicles, which recorded a moderate increase (+2.23%). This result may be attributed to improved road conditions, modernization of the vehicle fleet, and increased commercial activity, while simultaneously signalling the need for more intensive monitoring and control of freight traffic. On motorways, an increase in average speeds was recorded across all vehicle categories, particularly among heavy goods vehicles (+6.21%) and passenger cars (+1.85%). This increase may be associated with improved vehicle performance, more stable driving conditions, and an expanded motorway network; however, it also carries the potential risk of more severe crash outcomes. In summary, the results show that Serbia has recorded a reduction in speeds within settlements over the past decade, which is a positive indicator of the effectiveness of local measures; however, the gradual increase in speeds on motorways highlights the need for continued investment in enforcement measures and safety technologies to maintain stable levels of road traffic safety.

The data show that between 2014 and 2024 there was a substantial increase in the percentage of speed-limit violations across most vehicle categories, indicating a heightened tendency toward risky behaviour in traffic despite existing enforcement measures. Within settlements, the largest increases were recorded among heavy goods vehicles (+89.36%) and mopeds (+346.45%), which may be attributed to intensified commercial activity and weaker implementation of local enforcement measures. In contrast, a decrease was observed among motorcycles (−51.36%), which may be associated with stricter enforcement and increased awareness of risk among riders. On roads outside settlements, speed-limit violations increased dramatically among buses (+178.11%), mopeds (+265.08%), and passenger vehicles (+68.10%), indicating insufficient enforcement and the need for additional speed-control measures, such as automated systems or physical infrastructure. On motorways, the trend is likewise upward - particularly among heavy goods vehicles (+474.77%) and motorcycles (+108.29%). This suggests insufficient compliance with speed limits and a potentially higher level of road traffic risk. Overall, the data indicate that despite a slight reduction in average speeds in some zones, the frequency of speed-limit violations has increased, suggesting the need to strengthen preventive measures, enhance driver education, and expand the use of automated speed enforcement systems.

The use of mobile phones while driving has remained very high, with no meaningful improvement. Among passenger car drivers, only a minimal decrease was recorded (−0.10%), while slightly larger reductions were observed among heavy goods vehicle drivers (−3.76%) and bus drivers (−3.53%). However, these decreases are still insufficient to indicate a genuine change in driver behaviour. This highlights the need for strengthened enforcement and targeted awareness campaigns addressing the risks associated with mobile phone use while driving. In contrast, the use of seat belts shows a significant increase. On front seats, seat belt use among passenger car occupants rose from 70.3% to 85.8% (+22.05%), while heavy goods vehicles recorded an even higher increase (+76.85%). The most substantial improvement was observed among bus drivers, where seat belt use increased by more than +480%, representing a major institutional success in the implementation of safety regulations. Particularly noteworthy is the growth in rear-seat seat belt use among passenger car occupants - from only 4.0% in 2014 to 21.3% in 2024 (+432.5%), indicating a shift in passenger attitudes and the broader adoption of safe travel practices. Overall, the data show that seat belt use has become more widespread and socially accepted, whereas mobile phone use remains a persistent risk factor in road traffic. These findings confirm that educational campaigns and legal measures have had a positive impact on passenger protection, but also emphasize the need to direct greater attention toward digital risks while driving.

The indicators show remarkable progress in the use of child restraint systems. The overall usage rate increased from 18.4% to 60%, representing an improvement of more than 225%. The largest increase was recorded outside settlements (+278.88%), indicating heightened parental awareness of risks during longer trips and improved compliance with child safety regulations. Within settlements, usage increased from 17.2% to 56.1%, which is a positive signal in the context of urban safety and the effectiveness of educational campaigns. Although the results on motorways show a somewhat more moderate increase (+152.48%), they still demonstrate a stable upward trend and broader adoption of safety standards. These findings confirm that institutional measures, media campaigns, and traffic police enforcement have contributed significantly to the increased use of child restraint systems. However, continuous parental education and strict enforcement of regulations remain essential in order to reach European standards, where child safety system usage exceeds 90%.

STRATEGIC DOCUMENTS

According to the Law on Road Traffic Safety of the Republic of Serbia ("Official Gazette of the RS", Nos. 41/2009, 53/2010, 101/2011, 32/2013 – CC, 55/2014, 96/2015 – other law, 9/2016 – CC, 24/2018, 41/2018, 87/2018, 23/2019, 128/2020 – other law, 76/2023 and 19/2025), Article 11 introduced for the first time the obligation for the Government of the Republic of Serbia to adopt a Road Traffic Safety Strategy as the principal strategic document in this field. This article specifies that the Strategy must include a comprehensive assessment of the existing road safety situation, a clearly defined vision, long-term and short-term objectives, as well as key areas of action accompanied by deadlines for adopting the corresponding action plan.

Furthermore, Article 12 of the same law establishes the obligation to prepare an Action Plan, which defines in detail the measures and activities within key areas of work, the competent and responsible entities, implementation deadlines, and the required financial resources. In accordance with this legal provision, the Road Traffic Safety Strategy of the Republic of Serbia, together with its accompanying Action Plan, was adopted for the first time in 2015 for the period 2015–2020. After the expiration of this period, a new strategic document was adopted in 2023 for the period 2023–2030, accompanied by an Action Plan covering the period 2023–2025. It is important to note that a three-year gap occurred between the expiration of the first strategy and the adoption of the new one, during which no valid national strategic document existed. This interruption disrupted the continuity of systematic planning and road traffic safety management in the Republic of Serbia.

From the perspective of local self-government units, Article 13 of the Law on Road Traffic Safety prescribes the obligation of each local government to develop and adopt a local road traffic safety strategy and an annual road safety plan, in accordance with the national strategy and action plan. However, in 2014 only one local self-government unit had prepared and adopted a strategic document in this field. Ten years later, in 2024, a total of 96 local self-government units had developed their own strategic documents, of which a substantial number (77) had officially adopted them. This represents a significant advancement in the institutional approach to road traffic safety management at the local level.

The particular importance of this finding lies in the fact that, in the forthcoming period, all existing local strategies will be subject to individual and critical evaluation. The purpose of this analysis is to examine the extent to which local documents are aligned with national strategic objectives, whether they contain measurable performance indicators, and whether they reflect the specific safety challenges present in different contexts (urban, rural, and peri-urban). In this way, the study will provide a foundation for a critical assessment of the institutional maturity of the road traffic safety management system in the Republic of Serbia, with special emphasis on the local level as the key link in implementing a "bottom-up" approach[1].

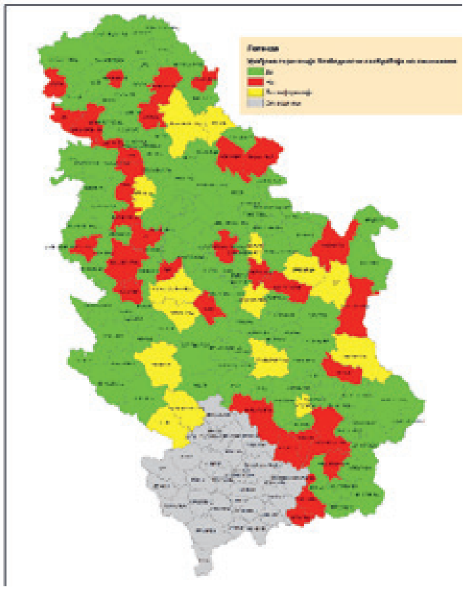

Figure 3. Map of Local Self-Governments in the Republic of Serbia That Have Developed a Strategic Document.

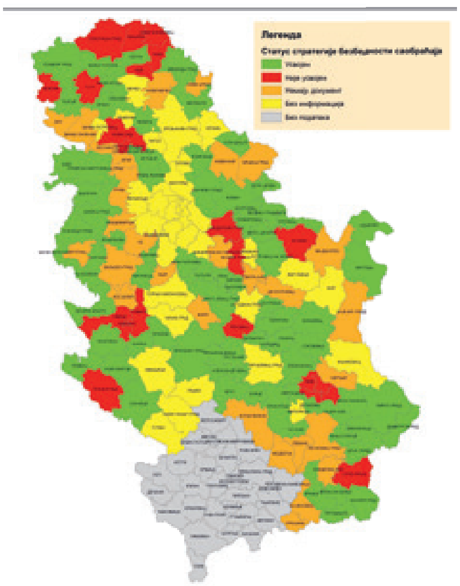

Figure 4. Map of Local Self-Governments in the Republic of Serbia That Have Adopted a Strategic Document.

DISCUSSION OF RESULTS AND CONCLUDING CONSIDERATIONS

The results of the study indicate that road traffic safety in the Republic of Serbia achieved certain institutional and analytical improvements between 2014 and 2024; however, these advancements have had only a limited effect on reducing the consequences of road traffic crashes. Although the total number of fatalities decreased by 7.83%, the number of injured persons increased by more than 8%, suggesting that preventive measures have not sufficiently reduced the overall severity of crash outcomes. These findings highlight the need to strengthen a comprehensive systemic approach that includes improved driver behaviour control, education, infrastructural interventions, and consistent monitoring of road safety performance indicators.

A particularly important observation is the increase in the weighted public risk (+12.15%) due to demographic decline, while the weighted traffic risk decreased by 22.91%. This contrast confirms the complex relationship between motorization, demography, and road traffic safety. The reduction in average speeds within settlements, combined with a simultaneous rise in the percentage of speed-limit violations outside settlements and on motorways, demonstrates that the problem lies not in the average value but in the distribution of risky behaviour. This indicates the presence of a significant group of drivers who systematically exceed speed limits, requiring more precisely targeted enforcement measures and sanctions.

A positive development is seen in the increased use of seat belts and child restraint systems—particularly on front seats and on roads outside settlements—where usage rose by more than 200%. This suggests the effectiveness of educational campaigns and institutional enforcement mechanisms implemented by the Road Traffic Safety Agency. At the same time, mobile phone use while driving remains high, indicating the need for a new approach to behavioural regulation and digital discipline in traffic.

A key institutional improvement is the growth in the number of local road safety strategies—from one in 2014 to 96 in 2024. This reflects the gradual development of a "bottom-up" management system that integrates local communities into the national road safety framework. In the coming period, all local strategies will undergo individual and critical evaluation to assess their quality, alignment with national objectives, and actual effects on road user safety.

In conclusion, although the results show a moderate reduction in fatal outcomes and substantial institutional progress, the Republic of Serbia continues to face challenges related to driver behaviour, infrastructural conditions, and enforcement of legislation. Achieving the vision of "zero fatalities" requires continued development of performance indicator monitoring, the introduction of measure effectiveness analysis through benchmarking and DEA models, and ensuring strategic continuity without institutional gaps. This study provides a foundation for further critical evaluation of local strategies

1 The "bottom-up approach" represents a road traffic safety management model in which initiatives, measures, and data originate from local self-government units and communities and are subsequently coordinated at the national level. This approach is based on decentralizing responsibilities and tailoring measures to local conditions, thereby ensuring greater effectiveness and sustainability of the system. Under this model, the state establishes the general framework and standards, while local actors ensure the concrete implementation of measures and monitoring of results on the ground.

and for the development of an integrated road safety management model in the Republic of Serbia.

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PROFESSIONAL PAPER

Behaviour of Young Drivers in Traffic in the Republic of Serbia

Miloš Pljakić
Prof. Dr Traffic Engineer, Faculty of Technical Sciences, Kosovska Mitrovica, Serbia, milos.pljakic@pr.ac.rs

Miloš Arsić
Prof. Dr Traffic Engineer, Faculty of Economics and Engineering Management, Novi Sad, Serbia, milos.arsic@fimek.edu.rs

Marina Leovac
Engineering Student, Faculty of Economics and Engineering Management, Novi Sad, Serbia, leoovac@gmail.com

Predrag Stanojević
Asst. Prof. Dr, Traffic Engineer, Faculty of Technical Sciences, Kosovska Mitrovica, Serbia, stanojevicpredrag@yahoo.com

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Abstract: Young drivers represent one of the highest-risk categories of traffic participants. Characteristic of this group is the presence of specific behavioral patterns and attitudes that often do not comply with safety standards. The aim of this study is to analyze the behavior of young drivers in traffic in the Republic of Serbia. The data collection method was conducting a survey via an electronic questionnaire. The Behaviour of Young Novice Drivers Scale was used. The questionnaire contains 44 items grouped into five categories examining different aspects of risky behavior. The categories include transitional violations, fixed violations, misjudgment, exposure to risk, and the influence of driver mood. An additional 13 questions used for analysis examine demographic characteristics of the respondents, such as gender, age, type of driver's license, etc. The sample consisted of 404 respondents aged 17-30 years (M = 22.95), of both genders. The obtained data were processed using the SPSS statistical package. The research results indicate significant differences in the behavior of young drivers who possess a probationary driving license compared to those who possess a full driving license. Respondents with a full driving license exhibited a higher level of risky behavior in the subscales of transient violations and risk exposure, compared to respondents who possess a probationary driving license.
Key words: young drivers, behaviour, traffic safety.

INTRODUCTION

The participation of young people in traffic, particularly as drivers, raises numerous questions regarding their safety, driving habits, and responses in everyday traffic situations. This category includes drivers aged 15 to 30. A lack of driving experience, combined with personality traits such as a tendency towards risky behaviour, susceptibility to peer influence on driving style, and the need to prove oneself, as well as physiological and developmental characteristics, overestimation of driving abilities, and limited awareness of the consequences of their actions, makes young drivers an exceptionally vulnerable group. [1] [2]

The issue of young driver casualties is a global concern, and summarising data from a wide range of sources is essential for understanding the problem as a whole. According to the Road Safety Report published by the European Commission, young drivers account for 18–30% of all traffic fatalities. [3] The relative mortality rate for young people aged 15–17 is 1.3, and for those aged 18–24 it is 3 per million inhabitants. [3] Research from the Netherlands indicates that, out of every 10 young drivers who lose their lives, as many as 6 of their passengers also die, and more than 7 other road users are killed in the same traffic accidents. [1]

The Governors Highway Safety Association (GHSA) analysed data from the Fatality Analysis Reporting System (FARS) over a 20-year period to determine whether the rates of all fatal traffic crashes involving drivers, particularly fatal crashes among drivers aged 15–20, decreased from 2002 to 2021. Unlike older drivers (aged 21 and over), young drivers are nearly four times more likely to be involved in a fatal crash, even though they drive less. [2] In Serbia, during the period 2019–2021, with regard to the role in traffic accidents, young people were most at risk as drivers and passengers in passenger vehicles and motorcycles. Of all fatally injured motorcyclists, 54% were young, while of all fatally injured passenger vehicle occupants, 34% were young passengers, and 21% of drivers of passenger vehicles were young. [4] In 2022, the number of fatally injured young people was 25.7% higher than in 2021, with the majority of fatalities (61.1%) and injuries (51.5%) occurring among drivers. [5] According to 2023 data, the number of young casualties decreased by 29.1% compared to 2022, with most fatalities (55.6%) and injuries (52.0%) occurring among drivers. [6]

The age range of 15–30 years is characterised by life-course dynamics that contribute to an increased risk of involvement in traffic accidents. Anatomical and developmental factors, including the incomplete maturation of the prefrontal cortex responsible for reasoning, self-control, risk assessment, and decision-making, influence changes in young drivers' behaviour, particularly in the mid-twenties, which falls within the domain of mental maturation and personality formation. [2] Consequently, the main factors contributing to traffic accidents evolve over time for each individual.

Gender differences are also evident, largely due to physiological characteristics. Research shows that male drivers aged 18–24 are three times more likely to be involved in fatal traffic accidents than female drivers. [7] These results reflect real-world traffic activity, however, it should be noted that male drivers participate more frequently as drivers of motor vehicles, and are proportionally more exposed to risks. [3] The influence of testosterone on male behaviour in this age group is crucial for understanding the behavioural patterns to which this group of drivers is prone. [1] Overall, 77% of all traffic fatalities involve male drivers. The percentage of fatalities is slightly lower among young people aged 15–17 (74%) and slightly higher among those aged 18–24 (82%). [3]

The first step in addressing this problem is identifying its causes, followed by an in-depth understanding. In the case of young drivers, understanding the causes of their behaviour, the origins of formed attitudes, and reasoning dynamics reveals a complex network of interconnected factors. In this study, in addition to the collected data on young drivers' everyday behaviour in traffic, which serves as key indicators of knowledge, awareness, and responsibility, the correlation between different behavioural patterns and the influence of demographic characteristics was also examined. Specifically, differences in behaviour between young drivers holding provisional licences and those holding full licences were investigated. This approach allows for the identification of young drivers' behaviour patterns based on self-reported actions. Understanding these patterns is a necessary condition for designing effective preventive measures that can significantly improve young driver safety and reduce the incidence of traffic accidents in this age group.

Identification of Young Drivers' Behaviour

Survey-based research represents a methodological approach that allows the examination of risky behaviours that increase the possibility of traffic accidents. Self-report instruments, such as the Driving Behaviour Questionnaire (DBQ), the Multidimensional Driving Style Inventory (MDSI), the Careless Driving Habits Scale, and the Behaviour of Young Novice Drivers Scale (BYNDS), have been applied among young drivers worldwide. [8]

Research on driver risk-taking behaviour led to the development of tools such as the DBQ, which is used to examine violations, errors, and lapses in driving. Although the DBQ was primarily developed for experienced and older drivers, it has occasionally been used in studies on young and novice drivers due to the lack of specific instruments. [9] The BYNDS was developed by Scott-Parker and colleagues in 2010 in Australia with the aim of providing a reliable and valid instrument for measuring risky behaviour specifically among young and novice drivers. [10]

Unlike the DBQ, which contains only three factors: errors, lapses, and violations, the BYNDS scale contains five factors: misjudgements (corresponding to the "errors" factor in the DBQ), transitional and fixed violations (both encompassed by a single factor in the DBQ), risk exposure (specific to young drivers), and driver mood. [9] The standardised BYNDS questionnaire has been validated and used to collect data on risky behaviour among young drivers in various countries, including Australia, New Zealand, and Colombia. [8]

Given that the BYNDS is one of the few instruments specifically designed to assess risky behaviour among young drivers and has already seen wide application in research, it was used as the primary instrument for assessment in this study.

METHODOLOGY

The data collection method involved conducting a survey via an electronic questionnaire. The Behaviour of Young Novice Drivers Scale [9] was used. The questionnaire contains 44 items, grouped into five categories examining different forms of risky behaviour. An additional 13 questions used for analysis investigate the demographic characteristics of the respondents, such as gender, age, type of driving licence, etc. The original version of the questionnaire was translated into Serbian and adapted to the specific characteristics of the area in which the research was conducted (e.g., driving on the right-hand lane is typical for Serbia, whereas the questionnaire assumes driving on the left-hand lane as the default model, etc.).

The BYNDS was developed out of the need for a tool specifically designed to measure self-reported behaviour of young novice drivers. The items in the original, and consequently in the revised BYNDS, were derived from the literature on traffic safety and Graduated Driver Licensing (GDL) restrictions. The original scale and its subscales demonstrated very high internal consistency. [10]

Measures

The Behaviour of Young Novice Drivers Scale, used to measure risky behaviour among young drivers, comprises five subscales within a total of 44 items. The subscales are:

- Transitional Violations (13 items; e.g., "You drove up to 10 km/h over the speed limit," or "You were talking on a mobile phone that you were holding in your hand").
- Fixed Violations (10 items; e.g., "You drove knowing that your blood alcohol level exceeded the legal limit," or "You did not use a seatbelt").
- Misjudgements (9 items; e.g., "You misjudged the speed of an oncoming vehicle when overtaking," or "You missed an exit or turn").
- Risk Exposure (9 items; e.g., "You drove at night," or "You drove while feeling fatigued").
- Driver Mood (3 items; e.g., "You drove fast when feeling in a bad mood," or "Your driving was influenced by negative emotions such as anger or frustration").

Respondents were asked to indicate how frequently they engaged in such behaviours. Responses were recorded on a five-point Likert scale ranging from 1 to 5 (1 – never, 5 – always). The respondents remained anonymous.

Statistical Data Analysis

The data obtained in this study were processed using the SPSS statistical package. The following procedures were applied:

- Descriptive statistics (frequencies, percentages, arithmetic mean, and standard deviation) were used to determine the degree of expression of variables in the sample.
- One-way analysis of covariance (ANCOVA) was employed to identify differences between young drivers holding a provisional driving licence and those holding a full driving licence.
- Chi-square test (test) was applied to identify risks in traffic accidents between drivers with a provisional licence and those with a full licence.
- Correlation analysis was conducted to determine the direction and strength of the relationships between variables.

Sample

The characteristics of the sample are presented in **Table 1**.

Table 1. Characteristics of the sample

Age	
Range (minimum – maximum)	17-30
Mean	22,95
Standard deviation	3,54
Gender	
Male (%)	227 (56,2)
Female (%)	177 (43,8)
Provisional driving licence	
Yes (%)	169 (41,8)
No (%)	235 (58,2)
Annual distance driven (km)	
Range (minimum – maximum)	0 – 100.000
Mean	12.444
Standard deviation	23.572
Traffic accidents in the past year	
Range (minimum – maximum)	0 - 3
Mean	0,08
Standard deviation	0,33
Risky situations in the past three months	
Range (minimum – maximum)	0 - 7
Mean	0,78
Standard deviation	1,27
Engine capacity of the vehicle	
Range (minimum – maximum)	900 – 3.500
Mean	1.506
Standard deviation	409

The sample comprised a total of 404 respondents, of whom 56.2% were male, thus constituting the majority. The age of the respondents ranged from 17 to 30 years. Most of the sample held a full driving licence (58.2%). Although the average annual distance driven was 12,444 km, the high standard deviation (23,572 km) indicates considerable variability among drivers, meaning that some respondents drove significantly more or less than the average. The mean number of traffic accidents in the past year was 0.08, showing that most respondents had not been involved in any accidents, with minimal deviation (standard deviation 0.33). On average, respondents reported 0.78 risky situations in the past three months, with a standard deviation of 1.27, indicating that such situations were generally rare, though some individuals experienced them more frequently. The mean engine capacity of the vehicles was 1,506 , with a standard deviation of 409 , reflecting moderate variability in engine size among the drivers.

RESULTS

The items within each factor of the scale were summed and comprised five subscales (transient violations, fixed violations, misjudgements, risk exposure, and driver mood). All subscales were reliable, demonstrating good internal consistency, with Cronbach's alpha ranging from 0.73 to 0.87.

Data from 2023 indicate that young people were most frequently involved in traffic accidents as drivers,

Table 2. Differences between young drivers holding a provisional driving licence and those holding a full driving licence

BYNDS	Provisional driving licence		Full driving licence		F(1, 400)	η²
	M	SD	M	SD		
Transient violations	28.24	0.71	30.36	0.60	**5.01***	.012
Fixed violations	22.88	0.29	22.67	0.24	0.33	.001
Misjudgements	16.42	0.29	16.21	0.25	0.26	.001
Risk exposure	30.50	0.55	34.74	0.46	**33.83****	.078
Driver mood	5.74	0.22	6.05	0.19	1.19	.003

Means were adjusted for gender and mileage. M – mean, SD – standard deviation. *p < .05; **p < .001.

with the highest unique risk indicator (URI = 72.0) compared to other age categories of drivers, reflecting their high exposure to severe traffic outcomes. [6] The aim of the study was to determine the impact of holding a provisional driving licence on the behaviour of young drivers (Table 2). A comparison between young drivers with provisional licences and those with full driving licences was conducted using various driver behaviour patterns measured by the BYNDS scale.

Table 2 shows that, after adjusting for gender and mileage, there were significant differences between young drivers holding a provisional driving licence and those holding a full driving licence in transient violations and risk exposure. Specifically, drivers with a full driving licence engaged in transient violations to a greater extent (e.g., "Driving up to 10 km/h over the speed limit" or "Driving at high speed on poorly lit roads").

Furthermore, a chi-square test (test) – where individuals who had not been involved in traffic accidents and had not committed violations were coded as "0", and individuals who had been involved in one or more traffic accidents and had committed violations were coded as "1" – showed no significant differences in traffic accidents between young drivers with a provisional licence and those with a full licence ((1, N = 404) = 1.53, p = 0.22).

The relationship between age, annual mileage, vehicle engine capacity, violations, participation in risky situations, and traffic accidents among young drivers was examined using Pearson's linear correlation coefficient. The results are presented in Table 3.

The results from Table 3 indicate significant correlations between drivers' age, fixed violations, and risk exposure. Additionally, there is a significant correlation between annual mileage on one hand and transient violations, fixed violations, misjudgements, risk exposure, participation in risky situations, and traffic accidents on the other hand. A significant positive correlation was observed between driver mood and transitional violations, fixed violations, misjudgements, and risk exposure. A positive correlation was also found between vehicle engine capacity and transitional violations, fixed violations, risk exposure, and involvement in traffic accidents.

All these forms of risky behaviour among young drivers, as measured by the BYNDS subscales, positively correlate with participation in risky situations. There is a significant positive correlation between transitional violations, fixed violations, and risk exposure on the one hand, and involvement in traffic accidents on the other.

DISCUSSION

The results of this study showed a significant difference in the behaviour and attitudes of young drivers holding a provisional driving licence compared to those holding a full driving licence. In conclusion, participants with a full driving licence exhibited higher levels of risky behaviour in the subscales of transitional violations and risk exposure, compared to participants with a provisional licence. These results indicate that the provisional driving licence, as a mechanism of control and restriction, has an

Table 3. Correlation between age, annual mileage, engine capacity, violations, risky situations, and traffic accidents.

Variable	1	2	3	4	5	6	7	8	9	10
1. Age	-									
2. Annual mileage	.20**	-								
3. Engine capacity	.20**	.26**	-							
4. Transitional v.	.06	.20**	.28**	-						
5. Fixed v.	-.12*	.12*	.11*	.25**	-					
6. Misjudgements	-.01	-.11*	-.04	.10*	.20**	-				
7. Risk exposure	.15**	.22**	.21**	.53**	.19**	.04	-			
8. Driver mood	.05	.07	.06	.43**	.19**	.34**	.30**	-		
9. Risky situations	-.09	.10*	.07	.21**	.12*	.22**	.18**	.24**	-	
10. T. accidents	.02	.15**	.18**	.14**	.19**	-.04	.10*	.08	.08	-

**p < .01; *p < .05.

extremely significant influence on the adoption of more responsible behavioural patterns during the early phase of acquiring driving experience. Upon transitioning to a full driving licence, these restrictions disappear, creating room for greater freedom, confidence, and lower discipline in driving behaviour.

Contrary to the differences observed across the subscales between these two categories of young drivers, the number of traffic accidents among them did not differ significantly. Given these data, it can be concluded that the presence of a provisional driving licence alone is not sufficient to reduce the number of traffic accidents, but it occupies a significant place within behavioural restriction mechanisms for young drivers and effectively reduces levels of risky behaviour among them, which may have a preventive effect in the long term.

Correlation analysis demonstrated significant associations between factors such as driver age, the number of kilometres driven, and engine capacity with various forms of risky behaviour and involvement in traffic accidents. The impact of age can be explained by the fact that the sample includes only young drivers (aged 17 to 30), among whom older participants tend to drive more independently and intensively, which may lead to a greater propensity for risky behaviour.

A higher number of kilometres driven means more time spent in traffic, but it may also lead to increased confidence or even an irrational assessment of one's driving skills. Additionally, young drivers operating vehicles with larger engine capacities during the early phase of driving experience, according to the data, are more prone to risky behaviour. Vehicles with larger engine capacities, and therefore higher power, allow for greater acceleration in a shorter period, which in young drivers can provoke a tendency towards aggressive and/or negligent driving behaviour.

The data also indicate that driver mood has a positive correlation with transitional violations, fixed violations, misjudgements, and risk exposure. This confirms that driving safety is influenced by psychological factors, not solely by technical vehicle-handling skills, which in itself is challenging for drivers in the early stages of driving experience. The category of young drivers is particularly emotionally sensitive and more prone to mood changes compared to other categories. Driving under the influence of negative emotions (e.g., borderline anger) induces a tendency to exceed the maximum permitted speed, while intense positive emotions (e.g., borderline euphoria) provoke the need for sensation-seeking while driving.

CONCLUSION

The original BYNDS scale contains five factors, while some previous studies, using exploratory factor analysis (EFA) and confirmatory factor analysis (CFA), have allocated the items into six or seven factors, showing variability in the factor structure across different samples and contexts. Although the sample in this study and previous research have a different number of factors, correlations between relevant factors show similar patterns, indicating consistency in the relationships of risky behaviour among young drivers.

A study conducted in Lithuania [11] on a sample of young drivers showed that, although the factor structure is different, correlations between the "Exposure to Risk" factor and the "Transitional Violations", "Misjudgements" and "Driver Mood" factors reflect similar patterns as in the sample of this study. A moderate correlation between the "Driver Mood" and "Exposure to Risk" factors is observed in both samples, indicating that negative emotions affect risky behaviour similarly across different cultural contexts. The "Misjudgements" and "Exposure to Risk" factors in both samples show a weak correlation, which also confirms a consistent pattern of behaviour. [11]

Comparing the results of research whose factor structure matched the structure of this study [9], a recurring pattern of correlations between factors is observed. The correlation with the highest value between the "Transitional Violations" and "Exposure to Risk" factors corresponds to the results of previous research. Additionally, a strong correlation is observed between transitional violations and driver mood, confirming the interrelation of these aspects of risky behaviour and indicating that the emotional state of the driver can be a significant predictor of transitional violations while driving. The type of driving licence has a significant correlation with the "Exposure to Risk" factor, which corresponds to the results of this study and indicates that young drivers with a full driving licence are more exposed to risks while driving. [9]

Limitations

Although the study included a relatively large number of participants, existing limitations should also be considered. Primarily, the results rely on participants' self-assessment, which carries the risk of poor self-evaluation and idealisation of responses. Participants were selected via the internet, which may lead to response bias (e.g., more precise answers from those particularly interested in the topic). Considering the shortcomings of this study, it would be highly valuable to also take into account objective data sources, such as police reports and data on actual driving behaviour obtained through continuous monitoring. Tracking young drivers over a specific period could provide detailed insight into the further development of driving habits after obtaining a full driving licence.

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REVIEW SCIENTIFIC PAPER

Cyber attacks on autonomous vehicles in the VANET computer network (attacks and protection)

Boris Kovačić
Pan-European University APEIRON Banja Luka

Zoran Ž. Avramović
University of Belgrade, Pan-European University APEIRON Banja Luka

Ivana Buzdovan
University of Adriatic Bar, Montenegro

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Abstract: Autonomous vehicles represent a revolution in mobility, but they raise the issue of security challenges. With their appearance and the introduction of the 5G network, traffic systems are becoming increasingly dependent on digital communication and real-time data processing. Connectivity through 5G networks and ad-hoc communication protocols makes them vulnerable to various forms of cyber attacks, which can threaten lives, property and public safety. The paper analyzes the threats to which autonomous vehicles are exposed within the VANET network (a specialized class of ad-hoc networks in which vehicles function as nodes in the communication network) in a 5G environment. The consequences of an attack can be: complete disabling of the operation of one or more vehicles in the system, traffic accidents due to false data or errors in algorithms, compromising the privacy of passengers and vehicle owners, disruption of traffic infrastructure, as well as loss of public trust. Special emphasis in the paper is placed on the consequences for traffic safety and potential protection measures.
Key words: autonomous vehicles, cyber attack, VANET computer network, 5G network, IEEE standards, communications: V2V, V2I i V2X.

INTRODUCTION

An autonomous vehicle is said to be a vehicle that moves from one point to another without human intervention. Autonomy is achieved by installing well-placed sensors that detect various objects such as obstacles on the road, pedestrians, traffic lights, stopping and movement of other vehicles.

Autonomous vehicles represent not only the future, but also the present on the roads around us. As with conventional vehicles, the safety of the passengers in the vehicle, as well as other road users, must come first. Autonomous vehicles are expected to make an even greater contribution to traffic safety, which is an important motive for their development. The systems that are currently installed in autonomous vehicles are not designed so that they can avoid obstacles on the road by maneuvering at the limit of the capabilities of the vehicle and the surface. For these purposes, a universal training ground based on ISO 3888-1 and ISO 3888-2 standards was adopted, which can be used to represent any situation in which there is an obstacle on the road in front of the vehicle that needs to be avoided. One of the solutions for drawing paths through the polygon is to use Bezier curves. (Stamenković, 2022)

The architecture of the autonomous vehicle is based on a hybrid solution. Architecture can be divided into three groups:

1. The perception level consists of a fusion of different sensors that collect information from the outside world using a suitable algorithm
2. The control software layer consists of vehicle control agents, route planner, navigator and driver. This level can also be called the level of thoughtfulness.
3. The physical level of the vehicle contains vehicle control controls, that is, more precisely, engine control, steering control, brake control and transmission control. The physical level of the vehicle can also be called the reactive layer.

VANET NETWORK ARCHITECTURE

The collection and processing of VANET network data can be divided into several levels, and all these levels together make up the network architecture itself. All data is stored and exchanged in the VANET Cloud architecture. The purpose of this architecture is to reduce errors that occur during data detection, delay and quality itself.

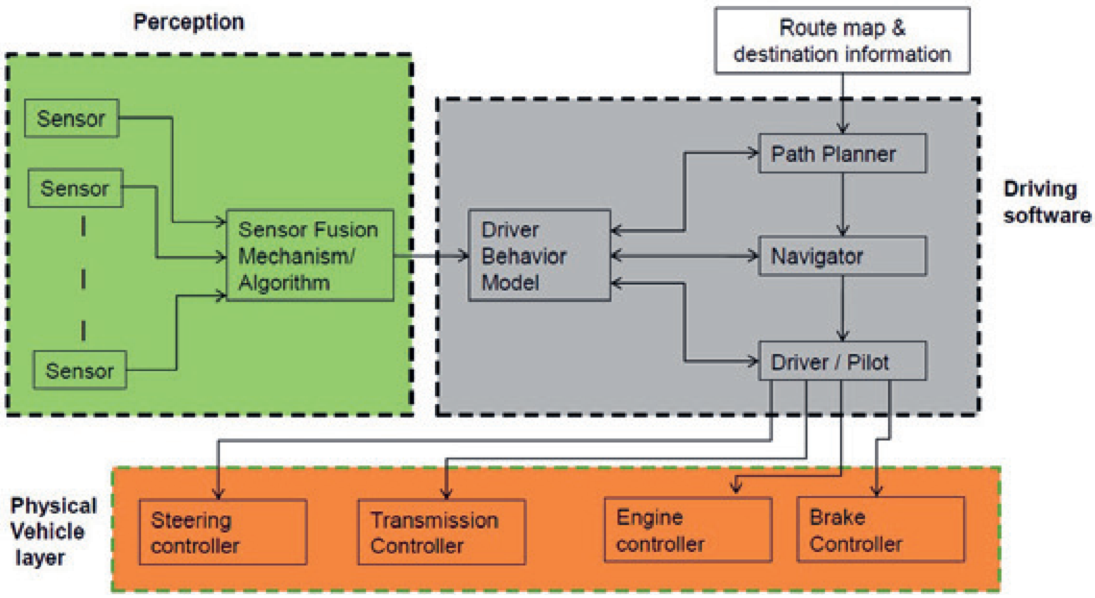

Figure 1. Sketch of autonomous vehicle architecture

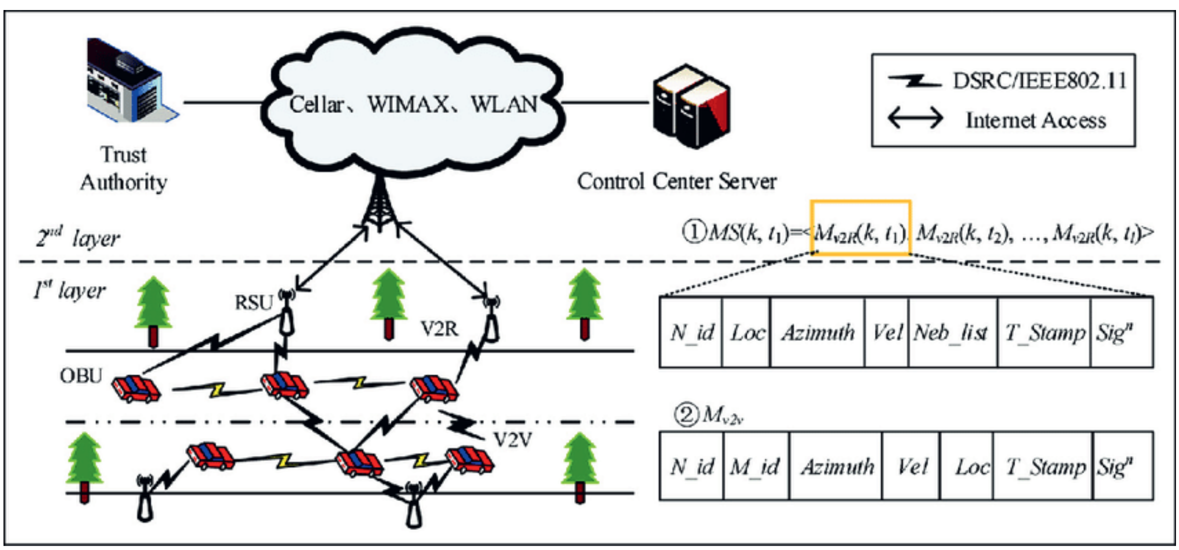

Figure 2. VANET network architecture (Xin, 2019)

There are three layers of architecture and they are: (Kovačević, 2020)

- *Traffic data collection layer*
- *Infrastructure as a service layer*
- *VANET Cloud layer*

Traffic data collection layer

This layer has the role of collecting data. All the data it processes and collects is obtained from the network itself. What is important to note is that the data it deals with must be processed in real time, i.e. almost instantaneously. Several parameters with which this layer works are: the speed of the vehicles themselves, the condition of the road and the traffic flow.

For the full operation of this layer of architecture, two interfaces are used, the communication interface, and the 'sensitive' data interface. The task of the sensitive data interface is to forward data to the Cloud. The communication interface is responsible for accessing traffic services in real time. Autonomous vehicles use 5G or higher network. It is preferable to have a network with the highest possible speed and the lowest possible latency.

Infrastructure as a service layer

The layer in which the infrastructure is used as a service has two sublayers, the physical resource sublayer and the virtualized sublayer. The physical resource sublayer groups the servers themselves depending on their characteristics. Servers are responsible for saving traffic data in real time. In addition, they allow access to various existing databases on traffic and road conditions.

VANET cloud layer

The VANET cloud layer, i.e. the cloud, is in charge of processing collected traffic data. After successfully processing all the data, the next step is to optimize the data prediction. Apart from predictions, it is important that the data sent to each vehicle is actually delivered to that vehicle and not to someone else. Predictive data in the cloud contains information such as travel time, traffic flow, speed, road closures and the like. (Ghoualmi-Zine, 2020)

The collection and processing of data is the center of this layer's work, and this is made possible by road-side detectors, RSU. RSU stands for Road Side Unit. The RSU passes such raw data to this layer using the UC 7420 device. It is a network device used to connect data collection devices and traffic lights using the UMTS network. The cloud offers two types of services. The first type of service is at the request of the user himself, and the second type of service is an automatic service. The on-demand service calculates data that is important to the user, such as travel plan planning and travel time. An automatic service is one that is essential for all road users, such as a traffic accident. Such events are sent to users themselves.

Data exchange in the VANET network

There are several models according to which messages are sent and received in a VANET network. Each model works in a different way, but they have in common that they provide a simple data exchange mechanism. There are three models of data exchange and they are:

- reactive data exchange,
- proactive data exchange and
- hybrid data exchange. (Kovačević, 2020)

Reactive exchange is based on protocols that work only when the user asks for some kind of information, therefore such protocols give better results. The main reactive protocol is AODV (Ad hoc on demand distance vector). Its task is to find a route to a destination, but only when that route is not known in advance. The working principle of this protocol is that each node within the network contains its own routing table. There are several pieces of information in that table, but the most important is information about arriving at the destination itself. In the event that a new, shorter route to the destination is discovered, AODV will save the new route and delete the old route.

Proactive data exchange is based on periodic updating of data, more precisely the routing table. The main protocol for this kind of exchange is the density-based routing protocol. The protocol itself ranks roads by density and arranges them in a hierarchy. This protocol works in real time. When it calculates the density on roads, it first sends a test packet, and only after that the route for the vehicle is selected.

Hybrid data exchange is based on an adaptive routing protocol, which is a combination of reactive and proactive. What this protocol takes into account is the speed and density of nodes. The density of nodes is calculated using LET (Link expiration time). If the nodes move at a high speed and their density is low, then the LET will be short, while conversely if the LET is relatively long, it means that the network is somewhat more static. The disadvantage of the adaptive routing protocol is that it uses a large number of periodic messages, which can lead to congestion.

Another type of protocol that exists are position-based protocols, the most famous of which is GSR (Geographic Source Protocol). As the name suggests, this protocol uses maps of cities and pulls information from them using RLS, reactive location service. Another positional protocol is GPSR (Greedy perimeter stateless routing) which has two modes of operation. One way is to forward the packets to the node that is geographically closest to it, and the other way is to forward the packets along a series of nodes. GPSR is unreliable and has high packet loss, so positioning protocols are not used in VANET networks.

Other protocols used by the VANET network are not mentioned in this paper, but only the most important ones.

EXAMPLES OF ATTACKS ON AUTONOMOUS VEHICLES:

Autonomous vehicles, which rely on artificial intelligence, sensors and wireless connectivity, represent a revolution in transportation — but also a new target for cyber attacks. Autonomous vehicles are vulnerable because they are connected to the Internet for navigation, communication with other vehicles and infrastructure. They use complex operating systems and firmware that may have security vulnerabilities. Cyber attacks can threaten the control of the vehicle, manipulate data or interfere with communication with other systems. The consequences that can be the result of a cyber attack are taking control of the vehicle, stealing personal data of passengers, disabling security systems, causing traffic accidents or traffic chaos.

In order to prevent the aforementioned cyber attacks, the industry works to improve cryptography and communication authentication, regularly improves and updates software, and issues system patches, introduces new and improves security protocols for V2V and V2I communication.

An attacker on an autonomous vehicle typically exploits a vulnerability in software, similar to an attack on a computer in a network. The steps it goes through during the attack are:

1. Target identification
2. System access
3. Taking control
4. Causing damage

Some examples of attacks are:

- In 2015, researchers Charlie Miller and Chris Valasek remotely hacked a Jeep Cherokee while it was driving, using a laptop and the Internet. They took control of the brakes, wipers, air conditioning and engine. The reaction of the manufacturer Fiat Chrysler is that it has recalled 1.4 million vehicles for safety upgrades.
- Ransomware attack on luxury vehicles in London in 2022, in which hackers stole 25 luxury cars using sophisticated hardware. With a targeted attack on contactless keys - by copying signals, vehicles are unlocked and started without a physical key.
- Cruise Company's Robotaxis vehicles in San Francisco 2022 clustered and stopped at an intersection, blocking traffic. Although the cause has not been officially confirmed, a hacker attack or software failure is suspected.
- Hackers managed to break into the software of the Stryker military vehicle. Hackers have managed to compromise the software of a US Army armored personnel carrier. Although a bullet can't penetrate it, a laptop can - which shows the vulnerability of even the most protected systems.
- Consumer Watchdog attack on Tesla vehicle in 2022 by non-profit group. The non-profit group managed to display the message "!Hacked!" on the screens of Tesla vehicles. The goal was to point out the vulnerability of the system and the need for better protection.

STANDARDS AND REGULATIONS

Manufacturers implement the "security by design" approach, which incorporates security requirements already in the development phase of each subsystem.

- Application of the ISO/SAE 21434 standard for engineering work on cyber security in vehicles.
- Complying with UNECE R 155 regulations on CSMS cyber security management system and R 156 on secure OTA software updates.
- Network segmentation within the vehicle to isolate infotainment systems from critical control units.

Regulation

- Manufacturers require from suppliers the application of ISO/SAE 21434 and regular audits of safety processes.
- They require the application of national regulations and directives, such as the EU NIS2, which contribute to the unique requirements for vehicle safety.

Communication protection and manufacturer's hardware solutions

The security of wireless interfaces and the CAN-bus network is essential for preventing unauthorized access.

- End-to-end encryption V2X (V2V, V2I) message.
- Using hardware modules for security key management (HSM) in ECU units.
- Two-factor authentication when accessing diagnostic ports.

SECURITY OF VANET NETWORKS

In VANET networks (Vehicular Ad Hoc Networks), attacks can be different and threaten the security, reliability and privacy of communication between vehicles and infrastructure. (Izet Jagodić, 2016) VANET networks are a special type of mobile ad hoc networks (MANET), where nodes are vehicles, and communication takes place at high speed in a dynamic environment. Attacks in VANET can be classified in several ways.

Types of attacks in VANET networks

1. By location of attack:

a) Attacks on vehicles (V2V):

- **Sybil Attack** – The attacker broadcasts multiple fake identities to create the illusion of a large number of vehicles nearby.
- **Bogus Information Attack** – Spreading false information (eg false information about a traffic accident).

b) Attacks on infrastructure (V2I):

- **Replay Attack** – Recording and resending messages to mislead the system.
- **Man-in-the-Middle (MitM)** – Interception and modification of communication between vehicle and RSU (Road Side Unit).

a) Attacks on vehicles (V2V):

Sybil Attack in VANET networks

Sybil Attack is a type of attack in which one attacking node (vehicle or device) simulates several different fake identities in the network. Instead of appearing as a single node, the attacker poses as multiple different vehicles, sending false information on behalf of each of these fictitious "nodes.".

Target of attack:

- Manipulation of network protocols that rely on the number of nodes or their location.
- Causing congestion, panic, or misdirecting vehicles.
- Undermining the reliability and security of the network.

Example in a VANET environment:

Imagine that there was a traffic accident in the tunnel. An attacker can create multiple Sybil identities and send messages like:

" Vehicle XY123 is located in front of the accident."
" Vehicle XY124 is also on site."
" Vehicle XY125 reports a huge crowd."

With enough messages like this, other participants in the network may think that the traffic accident is huge and decide to go the other way — which the attacker may want (eg to steal, avoid the police, or create chaos).

The consequences of a Sybil attack:

- False information in traffic (crowds, accidents, dangers)
- Violation of trust in the system
- Impeding the vehicle to make good decisions
- Potential accidents and economic damage

Sybil attack protection measures:

1. Authentication and certification of nodes:
   ◊ Each vehicle receives a unique digital certificate from the authority.
   ◊ Communication must be signed and verifiable.
2. Behavior detection:
   ◊ If several nodes come from the same location and send similar messages → possible Sybil warning.
3. Trast- systems **(*Trust Models*):**
   ◊ Building trust based on the node's behavior history.
4. Location verification:
   ◊ Comparing the reported location with GPS/RSU data. Sybil nodes usually have an identical physical location.
5. Limited number of identities per vehicle:
   ◊ Identity issuing systems allow only one or a limited number of valid certificates per vehicle at the same time.

Bogus Information Attack in VANET networks

Bogus Information Attack represents the intentional sending of false or altered information in the traffic network with the aim of causing the wrong behavior of other vehicles or the entire network.

It is a form of active attack, because the attacker actively sends messages with false content.

Attacker's goals:

- Misinforming other vehicles in order to create confusion, congestion, or traffic incidents.
- Impact on navigation, routing, or driving decisions.
- Creating an advantage for oneself (eg shortening the journey by avoiding a crowd that one falsely reported).

Examples in a real scenario:

1. The attacker sends a message:

"Nikola Tesla Street is closed due to an accident - please avoid!"

- Although in reality there are no accidents. Other participants start using alternative routes → the attacker avoids the crowd.

2. The attacker claims:

" Traffic is completely free on the highway"

- Although the highway is actually congested. This can cause more traffic jams or even traffic accidents.

Consequences of the attack:

- Wrong route decisions made.
- Increased number of accidents or traffic jams.
- Reduced trust in the system.
- Potential economic losses and security threats.

Protection measures against Bogus Information Attack:

1. Authentication of the message source:
   - Only authorized vehicles with valid certificates can send information.
2. Cross-checking of messages:
   - Messages are verified through several independent nodes.
   - If only one node claims something and the others do not – the message can be marked as suspicious.
3. Location check:
   - Messages are checked based on GPS location and RSU units - if the vehicle claims to be somewhere, but is not physically there, the message is rejected.
4. History of node behavior:
   - If the node has already sent incorrect information several times → its "trust" decreases → the messages are ignored.
5. Digital signatures and encryption:
   - It guarantees the integrity of the message and the identity of the sender.

Table 1. The difference between Sybil and Bogus attacks

Characteristics	Sybil Attack	Bogus Information Attack
Identity number	More fakes	Usually one
The problem it causes	Fake node count	False information content
Goal	Manipulation of the network structure	Disinformation from other participants

b) Attacks on infrastructure (V2I):

Replay Attack

Replay Attack (rebroadcast attack) in VANET networks implies that the attacker intercepts a legitimate message, saves it, and then later re-broadcasts it into the network as if it were new and valid.

The goal of the attack is to mislead the system that the old information is still current, which can cause incorrect vehicle behavior, congestion, or security risks.

Example of how the attack is carried out

1. Vehicle A sends a valid message:

" Accident on the road ahead, avoid!"

(with real timestamp)

1. The attacker intercepts that message and saves it.
2. After some time (when the situation has already been resolved), the attacker re-broadcasts the same message to the network.
3. Other vehicles interpret that message as new and react - even though the information is outdated and incorrect.

Targets of attack:

- Creating a false perception of the situation (eg an accident that no longer exists).
- Causing unnecessary road avoidance, congestion or traffic jams.
- Trying to hide the real situation (broadcasting old safety reports instead of the current danger).
- Breaking the security protocol that relies on signed messages - because the original message is valid.

Consequences:

- Loss of confidence in the system.
- Wrong decisions about the route or behavior of the driver.
- Reduced efficiency of traffic regulation.
- Potential traffic accidents.

Protection against Replay Attack:

1. Timestamps:
   - ◊ Each message contains the sending time.
   - ◊ The receiver checks whether the message is "too old" and ignores it if it is.
2. Nonce and Sequence Number:
   - ◊ Messages contain a non-repeating random number (nonce) or message number (sequence).
   - ◊ A repeated message is easily detected as a duplicate.
3. Session Tokens / Session contexts:
   - ◊ Each communication is tied to a session or time context.
   - ◊ Old tokens are no longer valid.
4. Cryptographic protection (signatures and encryption):
   - ◊ Signed messages with timestamp verification make this attack more difficult.
5. Smart RSU:
   - ◊ If a previously seen message appears in the same area - it can be marked as suspicious.

Table 2. Key Difference Between Replay Attack and Bogus Attack

Attack	Description
Replay Attack	Resending a previously valid message to cause an incorrect reaction.
Bogus Attack	Sending new but fake messages with wrong information.

Man-in-the-Middle (MitM) Attack in VANET networks

Man-in-the-Middle (MitM) attack in VANET occurs when an attacker places himself between two communication nodes (e.g. between two vehicles or between a vehicle and infrastructure), intercepts the communication, and has the possibility to:

- eavesdrops on messages,
- edit message content,
- forwards modified messages as if coming from a legitimate source.

The goal is that other nodes do not notice that the communication is not direct.

The places where MitM occurs in VANET are:

1. V2V attacker changes messages about accidents, road conditions, etc.
2. The V2I attacker falsifies the data sent or received by the RSU.
3. V2X – attacks on GNSS (eg GPS), Wi-Fi, DSRC, 5G or other communication channels.

Example scenario:

Vehicle A sends a message to vehicle B:

„Danger – ice on the road ahead. "

The attacker intercepts that message, changes it to:

„The road is clear – no problems whatsoever. "

Vehicle B receives a false message → continues without caution → possible accident.

Attacker's goals:

- Traffic diversion
- Spying on communication (eavesdropping)
- Entering false data into the network
- Disable authentication and trust

Consequences of a MitM attack:

- Violation of privacy
- Loss of data integrity
- The possibility of far-reaching sabotage
- Complete deformation of the traffic system in the area

MitM attack protection measures:

1. Traffic encryption
   - All messages are sent via TLS/SSL or other encrypted channel.
   - Even if the message is intercepted - the content remains unreadable.
2. Digital signatures
   - Each message is cryptographically signed (eg using ECDSA).
   - The recipient can verify authenticity and integrity.
3. Authentication with certificates
   - Each communicating party must have a valid certificate from a CA (Certification Authority).
   - Communication with unknown nodes is prevented.
4. Time-based verification and nonce value
   - Timestamps and random values are used to avoid Replay + MitM attacks.

Table 3. Key Differences: MitM vs. Replay vs. Bogus

Characteristics	MitM Attack	Replay Attack	Bogus Info Attack
Type	Interception and modification	Resending an old message	Sending a new, fake message
Message control	Full (read, change, send)	Limited (playback only)	Full (generates from scratch)
Goal	Deception or espionage	Confusion, misinformation	Creating a false situation

5. Intrusion detection (IDS/IPS)

- Systems that monitor traffic anomalies (eg unusual number of messages or deviation in behavior).

2. By the nature of the attack:

a) Active attacks:

- **Denial of Service (DoS)** – Overloading a network or resource to prevent communication. (Aleksandra Kostić-Ljubisavljević, 2024)
- **Message Tampering** – Changing the content of messages in transit.
- **Jamming** – Jamming radio signals to prevent communication.

b) Passive attacks:

- **Eavesdropping** – Eavesdropping on communications to collect data.
- **Tracking** – Monitoring of vehicle movement through the analysis of communication data.

a) Active attacks:

Denial of Service (DoS) Attack in VANET networks

Denial of Service (DoS) Attack in VANET networks represents an attempt to prevent normal communication between vehicles or between vehicles and infrastructure, through network, resource or software overload.

The aim of the attack is to make the system unavailable to legitimate users - either short-term or permanently.

VANET systems depend on fast, reliable and low-latency communication. If an attacker sends a large number of useless requests or messages, he can:

- block the wireless channel (DSRC, 802.11p, LTE-V/5G),
- occupy processor and memory resources in vehicles or RSU units,
- disable the processing of important messages (e.g. about an accident or braking).

Table 4. Examples of DoS attacks in VANET

Type of DoS attack	Description
Flooding Attack	The attacker sends a huge number of messages and thus occupies the channel.
Jamming Attack	Radio frequency jamming – real "noise" that blocks communication.
Malformed Packets	Sending messages with errors that cause the recipient's system to crash.
Resource Exhaustion	Memory, processor or bandwidth overload.

Goals of DoS attackers:

- Prevent the timely exchange of traffic data.
- Slow down or disrupt navigation systems.
- Cause accidents or chaos in traffic.
- Distract security systems in order to perform another attack (e.g. MitM or Bogus Attack).

Consequences of a DoS attack:

- Interruptions in V2V/V2I communication.
- Unprocessed critical messages (e.g. emergency braking).
- Decline of network infrastructure (RSU, control centers).
- Loss of confidence in vehicle security systems.

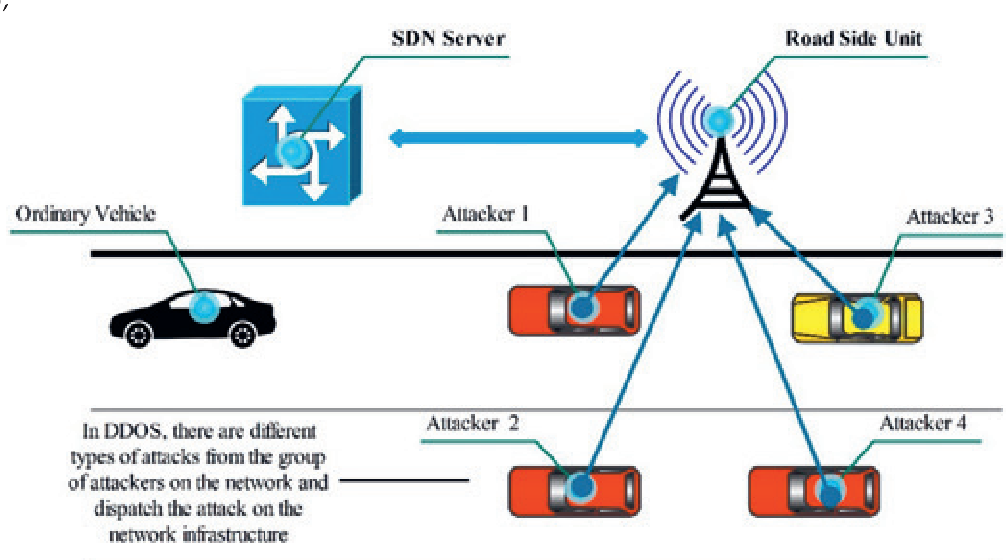

Figure 3. Example of a DDoS attack (Rashid, 2023)

Protection against DoS attacks:

1. Message rate limitation (Rate Limiting):
- RSUs and vehicles limit the number of messages they process from the same source in a certain time.

2. Detection of anomalies (Intrusion Detection Systems):
- Unusual number of messages, speed, packet size are monitored - suspicious patterns are detected.

3. Physical protection (Anti-Jamming):
- Using frequency hopping (Frequency Hopping), changeable channels and advanced antennas.

4. Filtering at the protocol level:
- Discard messages that do not respect the protocol (eg wrong length, incorrect headers).

5. Cryptographic protection:
- Although it does not prevent DoS directly, it prevents an attacker from broadcasting valid messages in large numbers without proper certificates.

Message Tampering Attack in VANET networks

Message Tampering is a type of attack in VANET networks in which the attacker modifies the content of a legitimate message in transit, before it reaches the recipient. The goal of the attack is to change the meaning or effect of the message without the knowledge of the original sender and receiver.

It is an active attack on data integrity, because the message appears as if it came from a legitimate source, but its content has been maliciously modified.

This type of attack occurs Between two vehicles (V2V), Between vehicle and infrastructure (V2I), Inside a malicious node that redirects messages, Combination with Man-in-the-Middle (MitM) attack

The vehicle receives incorrect information that the road is clear, even though it is ahead of accidents, which causes a possible collision.

Attacker's goals:
- Hiding or changing critical traffic information (eg accidents, roadblocks, weather conditions)
- Steering the vehicle in dangerous or wrong directions
- Creating chaos or bias in traffic (eg political or criminal intentions)
- Sabotaging communication or creating conditions for other attacks (eg DoS, Sybil, Bogus)

Consequences:
- Loss of data integrity
- Wrong driving decisions
- Injuries and accidents
- Loss of confidence in the VANET system

Protection against Message Tampering attacks:

1. Cryptographic digital signatures
- Each message is signed with the sender's private key.
- If the message is changed - the signature is no longer valid.
- Recipients can check whether the message is authentic and the integrity is preserved.

2. End-to-End encryption
- Messages are encrypted so that only the legitimate recipient can read or modify them.

3. Hash functions and MAC (Message Authentication Code)
- The message contains a hash value or MAC which is calculated based on the content and the key.
- Every message change changes the hash → easy to detect.

4. Timestamp and nonce verification
- A change to an old message (or its interception and modification) is detected if the time stamp is inconsistent.

5. Control via RSU and IDS system
- Messages are monitored and compared with other sources.
- If one message deviates from the majority, it is marked as suspicious.

In practice, the system receiving the messages must check the digital signature to detect this change.

Attacker's goals:
- Disabling vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) communication
- Preventing notifications about traffic accidents, conditions or emergency warnings
- Confusing autonomous vehicles
- Preparing the ground for other attacks (eg DoS, Sybil, MitM)

Consequences of Jamming attacks:
- Loss of all forms of communication (traffic, security, control)
- Increased risk of collision or traffic chaos
- Crash of the navigation and route planning system
- Disabling the operation of safety systems (ADAS, collision avoidance)

Protection against Jamming attacks:

1. Frequency Hopping Spread Spectrum (FHSS)
- Vehicles change communication frequency quickly → difficult for an attacker to follow

2. Direct Sequence Spread Spectrum (DSSS)
- The message spreads over a wide spectrum → better resistance to noise

3. Use of several channels (Multi-channel communication)
- Switching communication to less loaded channels

4. Detection on the physical layer
- Monitoring noise level, SNR (Signal-to-Noise Ratio), and other RF parameters
- Recognition of abnormal radio activity

5. Machine Learning IDS
- Using algorithms to recognize patterns that indicate interference

b) Passive attacks:

Eavesdropping attack in VANET networks

Eavesdropping is a passive attack in which an unauthorized attacker secretly eavesdrops on vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) communications, with the aim of gathering sensitive or private information, without intercepting or altering messages.

The attacker remains invisible and only listens/records, often in preparation for more serious attacks like Man-in-the-Middle, Replay, or Bogus Information.

Eavesdropping in VANET occurs:
- Between two vehicles communicating via wireless channels (DSRC, IEEE 802.11p, LTE-V, 5G)
- Between RSU and vehicle
- Near traffic infrastructure (e.g. traffic lights, parking lots, pumps)

Example: What can the attacker get?
- Vehicle identifier (eg vehicle_id)
- Location and direction of movement
- Time and driving route
- Content of messages such as warnings, reported incidents
- Maybe even personal or financial information if encryption is not used

Attacker's goals:
- Espionage: tracking the movement of a specific vehicle (eg police, officials, important personalities)
- Gathering information: for planning other attacks (MitM, DoS)
- Driver profiling: habits, routes, frequency of road use
- Endangering the privacy and safety of road users

Consequences of Eavesdropping attacks:
- Violation of privacy
- Leakage of sensitive information
- Loss of trust in VANET network security
- Potential misuse for criminal activities (tracking, theft, sabotage)

Protection against Eavesdropping attacks:
1. Communication encryption (Encryption)
- Use symmetric or asymmetric encryption for all V2V and V2I messages (eg AES, RSA, ECC)
- DSRC and 5G-V2X already support cryptographic protection

2. Digital signatures
- Even if someone eavesdrops on the message, they cannot modify or reuse it

3. Vehicle anonymization (Pseudonymity)
- Vehicles change their identifiers at certain intervals to avoid tracking

4. Controlled range of transmission
- Limit the range of wireless signals → less chance that someone nearby can eavesdrop

5. Physical Layer Security (PHY-Sec)
- Techniques such as beamforming and channel-based keying → communication only between direct participants

Eavesdropping simulation in Python:

```
def eavesdrop(packet):
 print(f"[👂] Wiretapped message:")
 print(f" ID: {packet.get('vehicle_id')}")
 print(f" Location: {packet.get('location')}")
 print(f" Event: {packet.get('event')}")
 print(f" Time: {packet.get('timestamp')}")

# Example of a "captured" message
sample_packet = {
 "vehicle_id": "NS-987-XY",
 "location": {"latitude": 44.8000, "longitude": 20.4600},
 "event": "TRAFFIC_JAM",
 "timestamp": "2025-07-10T14:22:00Z"
}

eavesdrop(sample_packet)
```

In reality, such an attack would be performed using SDR (Software Defined Radio) devices such as HackRF or USRP, which can "listen" to the DSRC/5.9GHz band.

Tracking attack in VANET networks

A tracking attack in VANET is the misuse of communication data to track the movement of a specific vehicle or driver in space and time. This is a passive or semi-active attack that violates privacy, but can also have security implications.

The attacker uses information such as Vehicle ID, GPS coordinates, time and speed of movement from V2V/V2I messages to form a profile and route of movement of the target vehicle.

Goals of Tracking attackers:
- Track the route and habits (e.g. where the driver lives, works, stops)
- Monitoring of vehicles of interest (official, police, VIP)
- Warning when the vehicle enters a certain zone
- Commercial exploitation (advertisements, marketing, sale of data)
- Preparation for physical attacks, theft or sabotage

Consequences of Tracking attacks:
- Gross violation of privacy
- Physical danger for the driver
- Manipulation of data for extortion, blackmail or attack

- Loss of trust in the system

Protection against Tracking attacks:

1. Pseudonymization of IDs
- Instead of a permanent Vehicle ID, time-limited pseudonyms are used
- Change of pseudonym takes place at intervals or in "silent" zones

2. Silent periods
- Vehicles periodically stop broadcasting messages for a short time → difficult tracking

3. Group communication
- Messages are sent on behalf of a group of vehicles → difficult to attribute to a single node

4. Local encryption and masking
- Details such as location and timestamp can be masked or rounded

5. Mix Zones

Special zones in which several vehicles change pseudonyms synchronously → the connection between the old and new ID is lost

3. By target of attack:

a) Attacks on confidentiality:
- The goal is unauthorized access to data (eg personal data of the driver).

b) Attacks on integrity:
- Modification of messages so that their meaning changes (eg changes in traffic messages).

c) Attacks on availability:
- Preventing normal communication between participants in the network.

d) Attacks on authenticity:
- Falsification of the identity of a participant in the network (eg the vehicle is presented as a police vehicle).

PROTECTING AN AUTONOMOUS VEHICLE FROM CYBER ATTACKS WITH THE HELP OF JUMP SERVER

The problem that occurs in all the previously mentioned cases is cyber attacks on autonomous vehicles.

Autonomous vehicles use a multitude of sensors, software, networks (V2X), cloud services and ECU devices. This makes them a potential target for cyber attacks, such as:

- **Remote Code Execution** (RCE)
- **Unauthorized Access** (ECU hacking)
- **Manipulation of the AI system** (e.g. "data poisoning" or adversarial inputs)
- **GPS spoofing / sensor hijacking**
- **Denial-of-Service (DoS)** on critical control modules

These attacks can:

- Take complete control of the vehicle
- Disable communication
- Cause direct physical damage or accidents

Security solution using Jump Server as a security filter

Jump Server (or *Bastion Host*) is an intermediary server that must be passed through in order to access critical systems, such as ECUs, vehicle cloud services or communication channels.

In an autonomous vehicle, it is placed between:

- Internal vehicle systems (CAN, ECU, AI modules, V2X communication)
- And all external communication points (cloud, OTA update, V2I, service providers, etc.)

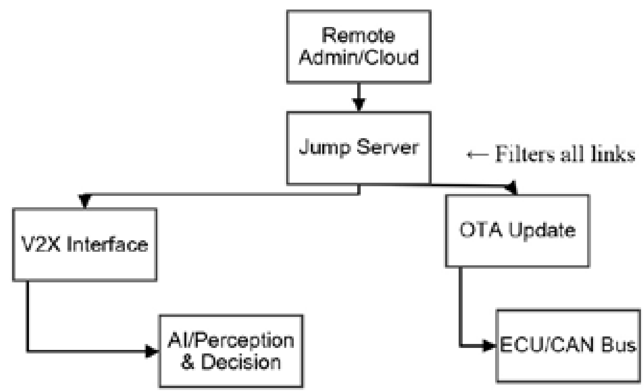

Figure 4. Protection architecture with Jump Server

Application in a real vehicle:

- Local (Edge): Jump server works in the vehicle itself as a "gateway firewall"
- Cloud-based OTA Access: Cloud must communicate through a centralized Jump server mechanism
- Servicer/Diagnostics: Must use time-limited tokens and access routes via Jump

The security policy provided by Jump Server:

- "Zero Trust": no one has direct access without verification
- "Least privilege": each access is limited by need
- "Audit everything": everything is logged and monitored

CONCLUSION

According to the above, it is clear that flawless cyber protection of autonomous vehicles is needed. The availability of access to autonomous vehicles through mesh networks and different communication channels complicates the cyber protection of vehicles. One of the solutions is the Jump server, as an innovative solution. Namely, the Jump server has been used in the protection of computer networks, primarily for channeling and protection of databases. It is mentioned as a possible solution in this paper, because in this way communication is channeled through one intermediary and in this way one point is defended. In addition, the progress of IoT devices, in terms of hardware, enables the use of better software solutions, such as Jump server.

In the future, the innovation that will be imposed in addition to the Jump server as a proposed solution for protection is a firewall, but a certain development of autonomous vehicles and sensors and IoT devices is required.

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PRELIMINARY REPORT

The impact of passively safe poles on the consequences of A traffic accident

Danislav Drašković
Faculty of Traffic of the Pan-European University Apeiron Banja Luka, danislav.m.draskovic@apeiron-edu.eu

Demeter Prislan
ICC DEMETER PRISLAN S.P. Dobravica 44, SI-1292 Ig, Slovenia, demeter.prislan@siol.net

Zoran Injac
Faculty of Traffic of the Pan-European University Apeiron Banja Luka, zoran.dj.injac@apeiron-edu.eu

Boris Mikanović
Faculty of Traffic of the Pan-European University Apeiron Banja Luka, boris.r.mikanovic@apeiron-edu.eu

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Abstract: All EU Member States have committed to targets to reduce the consequences of road accidents in the decade to 2030. In 2023, there were 20,400 road deaths in EU countries, down just 1% from the previous year. While this is a 10% decrease compared to 2019, which is the baseline for the 2030 strategic target, we can note that the trend has remained flat in several Member States, while others have seen an increase. Statistical trends in the Western Balkans show that the number of road deaths rose to 1,261 in 2023, an increase of 15 lives lost compared to previously published data. The region continues to lag behind the EU27 in road safety, underscoring the need for more effective measures. As one of the measures to increase traffic safety, the possibility of using passivly safe infrastructure, in particular lighting poles, traffic signal supports and equipment as an alternative to existing structures with the aim of reducing the consequences of traffic accidents that occur in the last run-off of the road is presented. The presented results are consistent with previous findings published in the literature on the severity of the consequences of traffic accidents with run-off of the road in several different environments. Most importantly, the results provide evidence that passive safety poles that absorb high energy (in accordance with EN 12767) contribute to the reduction of accidents in this type of traffic accident.

Key words: Traffic safety, passively safe pole, energy absorption.

INTRODUCTION

The consequences of traffic accidents represent a global problem. According to the World Health Organization (WHO), about 1.35 million people are fatally injured in traffic accidents worldwide each year, and 20 to 50 million people are injured, some of whom become permanently disabled [1].

Furthermore, traffic-related injuries are the leading cause of death among children and young people aged 5 to 29, and the twelfth leading cause of death across all age groups.

In addition to personal tragedies, traffic accidents also impose significant costs on society, including expenses related to emergency services, medical care, insurance, and more. For most countries, these costs amount to 1–3% of their gross domestic product (GDP), while in some less developed countries they reach up to 6% of GDP. Many people lose their lives in traffic accidents during their most productive years. Approximately 69% of fatal traffic accident victims are between 18 and 59 years old, while 23% are aged 60 or older.

In 2023, the EU recorded 20,400 road fatalities, representing only a 1% decrease compared to the previous year. Although this marks a 10% reduction compared to 2019 the baseline year for the strategic objective set for 2030 it can be concluded that the downward trend has remained steady in several member states, while an increase has been observed in others.

It should also be noted that, between 2012 and 2022, the total number of fatalities in traffic accidents decreased by approximately 11%. However, the share of fatal traffic accidents involving a single vehicle, compared to all traffic accidents, increased from 30% to 35%.[4]

Running off the road—that is, the unintentional deviation of a vehicle from its intended direction of travel—occurs frequently, and the literature often addresses this type of single-vehicle incident, commonly referred to as SVROR (Single Vehicle Run-Off Road).

Not every run-off-road incident necessarily results in human casualties or severe injuries; however, it is rare for the area beyond the roadway to be arranged in such a way that a vehicle can come to a relatively safe stop without posing risks to the occupants. The area adjacent to the roadway surface—referred to in foreign literature as the "roadside"—should be designed so that no hazards are present for vehicles that may leave the road due to loss of control. The concept of "forgiving roads" emphasizes the need to remove all dangerous objects from the safety zone. If certain objects must be located near the roadway—primarily street lighting poles and traffic sign supports—they must be designed so that they do not pose a serious threat to vehicle occupants in the event of a collision. These are known as passively safe roadside structures. If such design solutions are not feasible, hazardous objects within the safety zone must be protected by vehicle restraint systems.

Statistics show that approximately 20% of traffic-related fatalities result from vehicles running off the road and colliding with fixed roadside objects. [5] Nearly half of all fatalities in crashes involving fixed objects occur at night and frequently involve drivers under the influence of alcohol. Such accidents also occur due to excessive speed, driver fatigue, inattentiveness, or poor visibility.

According to the data [5], in fatal crashes the most common fixed objects struck by vehicles are trees (3,836 fatalities, 44%), roadside poles (1,027 fatalities, 12%), and safety barriers (844 fatalities, 10%).

In line with the sustainable development and road safety vision of the European Union and the United Nations, the Road Safety Strategy of the Republic of Srpska 2013–2022 identified the improvement of road safety in the Republic of Srpska as one of its key pillars, thereby directly contributing to the implementation of the United Nations 2030 Agenda for Sustainable Development (UN Agenda 2030). [6]

As a contribution to the "safe infrastructure" measure, interventions related to the pavement structure itself, as well as to the equipment installed along roadways, are taken into consideration. When examining roadside equipment, the use of passively safe poles is regarded as one of the most effective measures for improving overall traffic safety. When a vehicle collides with this type of pole, the pole is designed to yield in a controlled manner, thereby reducing injuries to vehicle occupants and other road users. As part of this measure, the gradual replacement of existing rigid poles with passively safe ones is recommended.

MATERIALS AND METHODS

This study addresses the current lack of literature concerning the safety implications of collisions with conventional roadside poles, such as metal, concrete, and wooden structures. While most previous research has focused either on general fixed-object collisions or on specific passive safety solutions, localized empirical analyses of real-world crashes involving standard, non-energy-absorbing poles remain limited. By examining the severity of real-world collisions involving these traditional pole types, the research aims to provide new insights into the consequences of outdated roadside infrastructure and to support the promotion of passively safe solutions compliant with EN 12767.

The study also analyzes the suitability of specific types of passively safe poles for particular locations, taking into account their ability to absorb impact energy, with the aim of reducing the severity of run-off-road crashes.

Currently, the Republic of Srpska does not maintain statistical records of traffic accidents in which a vehicle collided with a lighting or other utility pole. Therefore, one of the objectives of this research is to improve the traffic accident database to better understand the occurrence of vehicle-to-obstacle collisions.

Given the frequency and consequences of these incidents, the goal is to explore the potential for implementing forgiving infrastructure and remedial measures in high-risk areas to mitigate negative outcomes of the impact of vehicle–obstacle collisions mitigated through passively safe poles.

PASSIVELY SAFE POLES ACCORDING TO EN 12767:2019

General

The design of passively safe lighting columns in Europe is carried out in accordance with EN 40, while passive-safety performance is assessed according to the EN 12767:2019 standard. EN 12767:2019 defines passive-safety levels and establishes the rules for conducting and interpreting crash-test results under various impact conditions and vehicle speeds.

In the previous edition, EN 12767:2007 [8], poles were classified based on three parameters: impact speed, energy-absorption capability, and the level of occupant safety. In the revised 2019 edition, passive-safety classification is based on seven parameters:

- vehicle impact speed,
- energy-absorption capacity,
- occupant-safety level,
- backfill type of foundation for the poles,
- mode of pole failure,
- impact direction,
- impact angle,
- risk of roof indentation.

Parameters for Assessing Passive Safety

Vehicle Speed at Impact with the Pole

The speed class represents the speed of the vehicle at the moment of the experimental collision. According to the EN 12767 standard, two types of experimental crash tests are required: low-speed tests at 35 km/h, and higher-speed tests at 50, 70, or 100 km/h. A standard passenger vehicle weighing 900 kg and various types of pole foundations are used during these experimental tests. Low-speed crash tests are conducted to ensure satisfactory structural performance. High-speed crash tests enable the assessment of the pole's failure mechanism, its potential for energy absorption during impact, as well as the effects on the vehicle and its occupants.

Categories of Poles According to Their Energy-Absorption Capability

With respect to energy-absorption capacity, passively safe poles may be classified into three categories according to EN 12767:2019:

- HE poles (high energy absorbing) – poles that absorb a large amount of energy,
- LE poles (low energy absorbing) – poles that absorb a small amount of energy,
- NE poles (non-energy absorbing) – poles that do not absorb impact energy.

The behavior of the aforementioned poles during a vehicle impact is shown in Figure 1.

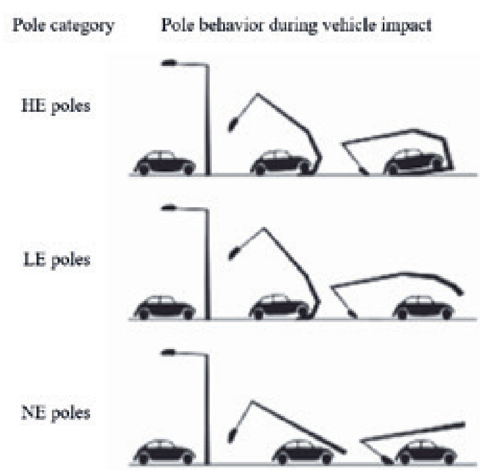

Figure 1. Categories of poles based on their energy-absorption capability

High-energy-absorbing poles (HE poles) significantly reduce the vehicle's speed after impact, and in some cases can even bring the vehicle to a complete stop. They are designed to deform in front of and beneath the vehicle upon impact, and in certain situations may even wrap around the vehicle.

Low-energy-absorbing poles (LE poles) provide only a modest reduction in vehicle speed following a collision. They are typically designed to fail in front of and beneath the vehicle before separating from their foundation.

When a vehicle collides with non-energy-absorbing poles (NE poles), the pole detaches at the foundation and is then thrown over the vehicle, ultimately falling near the base. The vehicle usually continues travelling with a certain reduction in speed and with relatively minor damage to the vehicle [9].

Some poles and supports for traffic signage offer considerable resistance when struck by a vehicle, while others provide only minimal resistance. Accordingly, there are categories of supports with high energy absorption, low energy absorption, and supports without energy absorption. This means that significant differences exist in the remaining kinetic energy of the vehicle—reflected in its post-impact speed—after striking a passively safe pole or signage support.

Table 1. Pole categories according to their energy absorption capability

Vehicle speed at impact, v_i [km/h]	50	70	100
Pole category	Vehicle speed after impact v_e [km/h]		
HE	$v_e = 0$	$0 \le v_e \le 5$	$0 \le v_e \le 50$
LE	$0 < v_e \le 5$	$5 < v_e \le 30$	$50 < v_e \le 70$
NE	$5 < v_e \le 50$	$30 < v_e \le 70$	$70 < v_e \le 100$

To determine the category of a pole with respect to its energy-absorption capability, the vehicle speed at the moment of the experimental collision (vi) and the vehicle speed after the collision (ve), measured at a specified distance from the pole, are recorded and then compared with the values provided in Table 1.

In the case of a collision at 100 km/h with a high-energy-absorbing passively safe pole (HE pole), the vehicle's post-impact speed will be at most 50 km/h, and such a support may even bring the vehicle to a complete stop.

In contrast to high-energy-absorbing passively safe poles, non-energy-absorbing poles offer significantly less resistance during a vehicle collision, leaving a relatively large amount of residual kinetic energy, which manifests in the vehicle's remaining speed. After impacting such a passively safe pole, the vehicle's speed is at least 70 km/h. The effect of deceleration on the human body in this case is minimal, with an ASI index even below 1. However, the problem lies in the fact that the vehicle continues moving at high speed. If there is another hazardous object in the stopping area, there is a high likelihood of collision with it. Numerous studies on the effects of rapid deceleration indicate that coming to a stop at a speed of 70 km/h is far from harmless.

Passenger safety level in the vehicle

The revised standard EN 12767:2019 defines five levels of occupant safety during a vehicle collision with a pole, labeled A to E, where A represents the highest level of safety. This is a change compared to the previous version of the standard EN 12767:2007, which defined four occupant safety levels, numbered 1 to 4.

Occupant safety levels are determined based on the values of two parameters: ASI (Acceleration Severity Index) and THIV (Theoretical Head Impact Velocity), obtained from the results of a large number of experimental collisions. The ASI value represents the calculated deceleration experienced by vehicle occupants during the collision.

Table 2 shows the corresponding ASI and THIV values that must be achieved during experimental collisions for each pole category according to its energy absorption capability.

Injuries from deceleration occur when a body moving at high speed is suddenly stopped, causing various types of trauma. At a speed of 50 km/h, a stop occurring within 0.1 seconds generates very high deceleration forces, potentially up to 30g, which can cause serious injuries such as shock, brain concussion, abrasions, sprains, skin lacerations, rupture of internal organs, bone fractures, respiratory and circulatory paralysis, bleeding, and organ damage.

If the stopping time is extended to 0.7 seconds, the deceleration force is significantly reduced, which can decrease the severity of injuries. However, even with longer deceleration times, injuries can still occur, though they may be less severe compared to a stop within 0.1 seconds. A collision lasting less than 0.2 seconds for a body moving at 100 km/h can be fatal. Sudden deceleration can generate substantial forces on the human body, measured in gravitational acceleration (g). If the deceleration duration is less than 0.2 seconds, the peak sustained deceleration is around 30g when the person is facing forward. Such forces can result in severe injuries, including shock, brain concussion, rupture of internal organs, and even respiratory and circulatory arrest. The human body can withstand slightly higher forces, up to 35g, if oriented with the back facing the acceleration line, but even in this case, the risk of serious injury remains high.

From the above, we can conclude that even deceleration alone can be dangerous to the human body. In the case of a collision with a conventional rigid support,

Figure 2. Vehicle stopping with an impact speed of 46 km/h, impact duration 0.5 seconds, deceleration 138 m/s²

Source: Test impact on a rigid pole – Španik test site, Murska Sobota, 2009

there is an additional problem: the deep intrusion of the conventional equipment post into the vehicle body. The smaller the contact surface, the deeper the intrusion, assuming all other factors remain unchanged. Therefore, it is remarkable that road authorities are still debating whether to implement a passively safe post or a standard rigid road equipment post.

APPLICATION OF PASSIVELY SAFE POLES

General

This chapter analyzes the justification for applying specific types of passively safe poles for a given road section. When selecting the type of pole, several factors must be considered, such as the pole's failure mode, occupant safety, risks to other road users (e.g., in urban areas), the speed limit on the considered section, the presence of roadside objects such as bridges or walls, vehicle damage, and others.

Non-energy-absorbing poles (NE poles)

Non-energy-absorbing poles (NE poles) are recommended in areas where high speeds are allowed and there are no nearby objects or pedestrians. Using this type of pole achieves the highest level of safety for vehicle occupants because, after a collision, the vehicle continues to move with only moderate deceleration and minimal damage compared to other types of poles. In locations where there is no risk to other road users, this type of

Table 2. Determination of passenger safety level in the vehicle

Pole categories based on energy absorption	Passenger safety level	Speed (maximum values)			
		Mandatory low-speed crash test at 35 km/h		Crash tests at speeds of 50 km/h, 70 km/h, and 100 km/h	
		ASI	THIV km/h	ASI	THIV km/h
HE/LE/NE	E	1,0	27	1,4	44
HE/LE/NE	D	1,0	27	1,2	33
HE/LE/NE	C	1,0	27	1,0	27
HE/LE/NE	B	0,6	11	0,6	11
NE	A	Values for ASI and THIV are not specified.		No measured values for ASI and THIV.	

pole is the best choice for vehicle occupants, as the impact is usually very brief, and the vehicle continues to move after the collision. Non-energy-absorbing poles are not recommended near pedestrian zones, bicycle paths, or trees.

High-energy-absorbing poles (HE poles)

Poles capable of absorbing energy (HE and LE poles) are recommended in locations where there is a possibility of secondary collisions and risks to other road users. High-energy-absorbing poles can absorb a large amount of energy, causing plastic deformation of the pole and bending of the pole under the vehicle. Such poles significantly decelerate and stop the vehicle during a collision, reducing the risk of secondary impacts with roadside objects, trees, pedestrians, and other road users. The use of this type of pole is recommended in areas where there are no obstacles around the pole. It should be noted that after a collision with this type of pole, the vehicle may still move briefly while the pole deforms. A critical HE pole stops the vehicle completely.

Low-energy-absorbing poles (LE poles)

Low-energy-absorbing poles possess characteristics between high-energy-absorbing and non-energy-absorbing poles. They are designed so that upon collision, they fail by yielding in front of and beneath the vehicle before detaching from the foundation, unlike non-energy-absorbing poles. The speed of the vehicle striking such a pole is reduced, and vehicle damage is less than that in a collision with a high-energy-absorbing pole.

RESULTS AND DISCUSSION

A significant number of studies, based on multiple methods of data collection and analysis, have identified various factors contributing to accidents and injuries involving collisions with poles.

In Flanders (Belgium), the Flemish Road Administration has recommended the installation of HE-type passive safety poles since 2010, depending on the speed limit, distance of installation from the roadway, and the presence or absence of protective barriers. Specifically, HE-type passive safety poles are recommended in clear zones when the speed limit exceeds 50 km/h and whenever no protective barrier is present.

For roads with a speed limit of 50 km/h, these poles are recommended whenever the distance from the roadway is less than two meters and no protective barrier is present. Their installation is also recommended in areas with a high risk of vehicle collisions with lighting poles, such as sharp curves, highway exits and entrances, and roundabouts (AWV, 2010).

High-energy absorbing poles (HE) should not be used on roads where vehicles travel at 30 km/h, in coastal areas with frequent storms, or for public lighting fixtures that need to be installed at heights exceeding 12.5 m (the maximum height for high-energy poles), as highlighted in the recommendations of the Flemish Road and Traffic Agency (AWV, 2010). For speeds of 30 km/h or lower, passive safety poles are not recommended because, for traditional poles, material costs in low-speed collisions are lower, and the risk of injury is considered sufficiently low (AWV, 2014).

Our efforts support the current Flemish policy regarding passively safe infrastructure, including the installation of lighting poles and traffic signal supports, through the concept of "forgiving road safety" to mitigate the severity of run-off-road (ROR) crashes on Belgian roads. Further development of road inventory systems should provide additional and improved data on road characteristics and traffic accidents. This data would create a foundation for further research, leading to more precise recommendations for the most effective enhancement of road safety.

Finally, the study by Albuquerque and Awadalla [10] aimed to quantify the probability of fatal injuries in single-vehicle run-off-road (SVROR) crashes using multivariate logistic regression models. According to the results, crashes involving W-beam guardrails showed the lowest probability of driver fatality compared to other crashes with fixed objects (trees, poles, and concrete barriers).

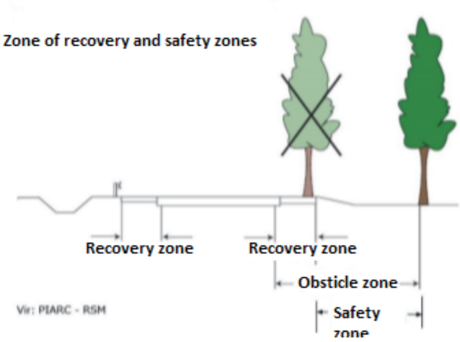

Figure 3. Safe road principle – the width and length of the safety zone depend on the type of roadway and vary from country to country

CONCLUSION

The prevention of traffic accidents and the reduction of their consequences are key objectives in the field of road safety. One way to mitigate the consequences of such accidents is the implementation of passively safe infrastructure along roads, particularly lighting poles and traffic signal supports, with appropriate energy-absorbing properties upon vehicle impact, as a contribution to the measure of safe infrastructure.

Input data represent a major limiting factor in efforts to study the contribution of roadside objects to the outcome of collisions, especially when dealing with minor injuries or cases where no injury occurs. This limitation implies that results must be carefully interpreted, and further work is needed to collect data on impacts with passively safe poles where only material damage occurs, in order to develop a more flexible and comprehensive specification model. It is essential to emphasize the need for continued data collection on impacts as well as on road equipment, with the aim of expanding the database for further research that will provide updated recommendations for the most effective enhancement of passive road safety. The selection of passively safe poles may not prevent a traffic accident, but it can reduce its consequences, help save lives, and lower material costs.

Additionally, the selection of the type of passively safe poles for a particular road section depends on several factors, such as the manner in which the poles fail, the safety of vehicle occupants, risks to other road users, the speed limit on the section under consideration, the presence of roadside objects, vehicle damage, and other factors.

Non-energy-absorbing poles (NE poles) are recommended in areas where high speeds are permitted and where there are no nearby objects or pedestrians. Using this type of pole provides the highest level of safety for vehicles and results in the least damage to the vehicle compared to other types of poles. However, these poles are not recommended near pedestrian zones, bicycle paths, or trees. Energy-absorbing poles (HE and LE poles) are recommended in locations where there is a risk of secondary collisions and potential danger to other road users.

The classification of passively safe poles according to the revised 2019 standard is based on seven parameters; therefore, pole labeling is more detailed than before, enabling a better selection of the appropriate pole type for a specific road section.

Considering that, in the Republic of Srpska, official statistics only track road accidents classified as "vehicle collision with roadside object", it would be beneficial to also monitor accidents involving collisions with roadside poles, trees, and other objects. Currently, existing accident databases do not specify the type of object involved in the collision (such as a guardrail, lighting pole, tree, or other solid object), unlike practices in databases of other countries where the exact type of object struck by the vehicle is recorded. We believe that, by utilizing today's IT technology, existing databases can be improved within a reasonable timeframe, resulting not only in more accurate records but also in a solid foundation for implementing measures to enhance road safety.

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ORIGINAL SCIENTIFIC PAPER

Stochastic analysis of gender-differentiated ethical patterns in the function of optimizing traffic and work processes

Nina Uremović
Associate Professor, Faculty of Business Economics, Pan-European University Apeiron, Banja Luka, Republic of Srpska, Bosnia and Herzegovina, nina.d.uremovic@apeiron-edu.eu; ORCID ID: 0000-0001-5445-2262

Radmila Pejić
Assistant Professor, Faculty of Business Economics, Pan-European University Apeiron, Banja Luka, Republic of Srpska, Bosnia and Herzegovina, radmila.v.pejic@apeiron-edu.eu; ORCID ID: 0009-0003-8742-6003

Mirjana Landika
Full Professor, Faculty of Business Economics, Pan-European University Apeiron, Banja Luka, Republic of Srpska, Bosnia and Herzegovina, mirjana.f.landika@apeiron-edu.eu; ORCID ID: 0000-0002-1495-2462

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Abstract: Ethical behavior in traffic and the workplace exhibits noticeable gender differences, which are not determined solely by biological characteristics but also by social norms, roles, and expectations. This study analyzes the stochastic relationship between gender and expressed ethical attitudes using appropriate statistical methods, aiming to identify behavioral regularities. The results indicate statistically significant differences, with women showing greater consistency in applying ethical norms both in traffic and in work environments. The findings can serve as a basis for developing targeted educational and regulatory measures to improve traffic safety and efficiency in work processes while considering gender-specific characteristics.

Key words: ethics, gender differences, traffic, work environment, binary logistic regression.

INTRODUCTION

Ethical behavior forms the foundation for building trust, safety, and efficiency in modern traffic systems and work environments. In societies characterized by complex interpersonal relationships and increasing demands for responsible conduct, understanding patterns of ethical decision-making becomes crucial for enhancing system functionality, preventing risks, and establishing sustainable standards.

A particular challenge lies in identifying and analyzing gender differences in ethical behavior, as gender—as a social construct—shapes the ways individuals perceive norms, make decisions, and respond to ethical dilemmas. Numerous studies in the field of traffic indicate differences in risk perception and compliance with traffic regulations between men and women. In the work context, these differences manifest in terms of professional responsibility, communication, and attitudes toward rules and authority. Due to the complex relationships between gender and ethical behavior, stochastic analytical models were applied in this study to measure variable behavioral patterns. The aim of the research is to identify patterns of ethical behavior that differ by gender and to examine how these patterns can be utilized to improve traffic and work processes. Particular emphasis is placed on the use of statistical methods that help better understand ethical decision-making in real-world circumstances. A multidisciplinary approach integrating sociological, psychological, and statistical perspectives enables a comprehensive analysis of the complex relationships between ethics and gender, with the potential to contribute to the enhancement of professional standards, safety, and organizational efficiency.

LITERATURE REVIEW

The study of ethical behavior in modern societies is gaining increasing importance due to the dynamic changes in work and social relationships. Ethical conduct in traffic and the workplace has long been the subject of interdisciplinary research. Existing literature indicates that ethical behavior is not determined solely by individual traits but also by broader social, cultural, and structural conditions, which often vary depending on gender.

Research in the field of traffic shows that men and women differ in risk perception and ethical behavior. On average, women are less likely to violate traffic regulations and less frequently involved in traffic accidents caused by aggressive behavior. These differences have significant implications for ethical and safety practices in traffic. According to studies by Özkan and Lajunen (2006), men are more likely to exhibit risky driving behavior and are less inclined to comply with traffic rules, while women demonstrate higher levels of caution and adherence to moral norms. These differences are often interpreted through the lens of gender socialization – women are taught caution and responsibility, whereas men are encouraged to be confident and risk-taking.

Sociological approaches, particularly those inspired by gender theory, indicate that traffic behavior does not stem from biological differences but from accepted social norms regarding “feminine” and “masculine” behavior (Connell, 2005). In parallel, moral development theories suggest that women may be more inclined toward an ethic of care and interpersonal responsibility, which is reflected in more careful behavior in traffic (Gilligan, 1982). Such approaches highlight the need to analyze ethical behavior not only at the level of individual choices but also in terms of deeper social and psychological patterns.

In the workplace, gender differences in ethics are also well documented. The work environment represents a complex setting in which ethics manifests through professional norms and interpersonal relationships. Gender differences in professional ethics are often reflected in varying styles of communication, decision-making, and conflict management. According to numerous studies, women more frequently demonstrate sensitivity to moral dilemmas, show greater adherence to rules, and are more willing to report unethical actions (Loo, 2003).

Gender differences in workplace ethics and behavior are further influenced by women’s position within organizational hierarchies. Research by Eagly and Carli (2007) indicates that women in leadership positions are more likely to consider the opinions of others, and their leadership style is based on mutual trust, dialogue, and collective responsibility. At the same time, however, they face double standards and higher moral expectations (Catalyst, 2020).

The application of stochastic models in the study of ethical behavior allows for a quantitative assessment of the probability of certain reactions or deviations, without relying on strict deterministic laws, but by modeling behavioral patterns useful for prevention and process optimization.

In the domestic literature, this topic remains insufficiently explored. Existing studies primarily address traffic safety and issues of gender equality in work environments but rarely include the ethical dimension in both contexts. Therefore, this study aims to contribute to this gap through an interdisciplinary, empirical, and statistically grounded approach.

RESEARCH METHODOLOGY

The empirical basis of this study rests on the hypothesis that there is a causal relationship between an individual’s behavior in two distinct environments—namely, the workplace and the traffic environment—as well as a gender-conditioned causal relationship.

A quantitative-statistical approach based on stochastic analysis was applied in this research, enabling the examination of the probability of ethically relevant behavioral patterns occurring in different contexts. The study was conducted on a sample of 104 respondents, evenly distributed by gender, employment status, and age. The questionnaire, presented below, was administered electronically. A sufficient number of respondents completed the survey, allowing the research results to be formed on the basis of collected empirical data, with the structure of responses enabling further research procedures and the drawing of valid conclusions.

Illustration 1. Example of the survey questionnaire (authors)

ETHICS

Category	Options
1. Age	Up to 25 years / 25–40 years / 41–65 years / Over 65 years
2. Place of upbringing	Village / Suburban area / City
3. Gender	Male / Female
4. Highest level of education completed	Primary school / Secondary school / College or university / Master’s degree / Doctorate
5. Highest level of education of your mother	Primary school / Secondary school / College or university / Master’s degree / Doctorate
6. Highest level of education of your father	Primary school / Secondary school / College or university / Master’s degree / Doctorate
7. Employment status	Student / Employed / Unemployed / Homemaker / Entrepreneur / Retired
8. Position at work	Assistant worker / Executive worker / Lower management / Middle management / Senior management / Entrepreneur
9. Marital status	Married / Cohabiting / Single / Divorced / Widowed / Living with family of origin
10. Driver status	No / Yes, passive (licensed but rarely drives) / Yes, active
11. Knowledge of ethics	Yes / Heard of the concept but not certain / No
12. Do you consider yourself an ethical person?	Yes, completely / Partially, everyone deviates sometimes / No, why should I, most people aren’t

13. Express your attitude towards behavior in traffic

Answer / Question	I agree	I agree, but sometimes allowed	Every rule has exceptions	If it does not endanger anyone, deviation is allowed	If there is no possibility of punishment, then not	I disagree
Seat belt should be fastened						
Right of way should be respected						
Pedestrians crossing at un marked locations should be allowed						
Overtaking on a solid line is not allowed						
Speed limits should be respected						
Parking bans should be observed						
Mobile phone should not be used, except as permitted						

14. Express your attitude towards behavior in the workplace

Answer / Question	I agree	I agree, if circumstances require	Only if necessary	If there will be no sanctions, why bother	I am not valued at work anyway, why bother	No
Arrive on time and stay until the end of working hours						
Working hours should be used exclusively for work-related activities						
Workplace resources should be used rationally (as if we bought them ourselves)						
Colleagues should be treated respectfully						
Superiors should be obeyed						
Work as if you are work ing "for yourself"						
Help others when needed						
Stay longer at work if the job requires it						

The structure of responses regarding behavior in traffic and workplace environments can be illustrated as shown below.

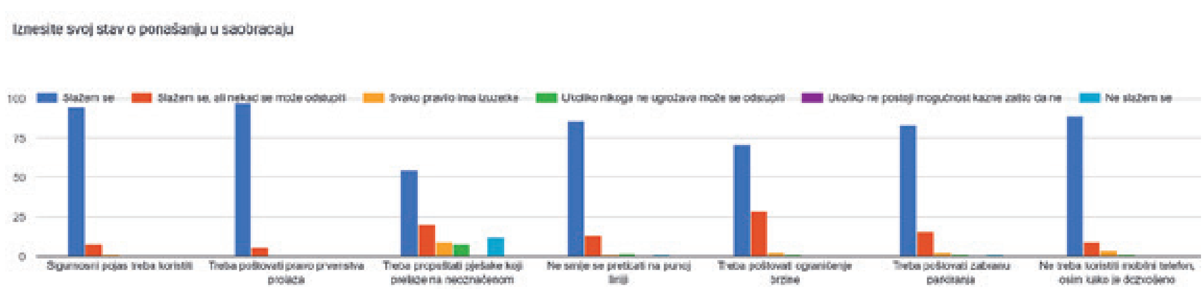

Figure 1. Respondents' attitudes toward traffic ethics (authors)

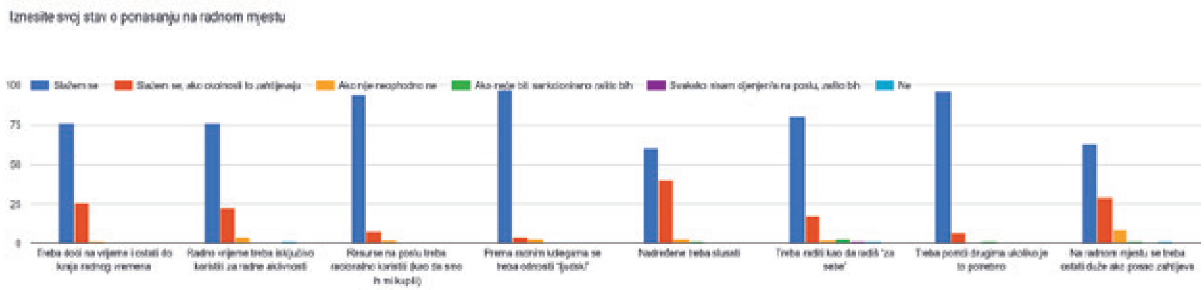

Figure 2. Respondents' attitudes toward workplace ethics (authors)

The aim of the methodology is to identify the probabilities and regularities that show to what extent and in what way ethical behavior varies depending on gender, with a special focus on interactions between the work and traffic contexts. This approach enables a deeper understanding of gender-conditioned behavioral patterns and contributes to the foundation for recommendations regarding ethics in traffic, the workplace, and regulations governing specific behaviors.

For the analysis, the binary logistic regression method was used, which predicts the likelihood of an individual exhibiting certain behavior in traffic based on gender and workplace ethical components.

The binary logistic regression model uses empirical data to explain the probability of a specific outcome occurring. In the model, the dependent variable is the likelihood that an individual exhibits a particular behavior as a participant in the traffic process, while the independent variables include gender and the individual's ethical code in the workplace.

The binary logistic regression model allows us to answer the question of the probability that an individual will exhibit a certain behavior during the traffic process, considered a traffic violation, taking into account their gender and ethical code in the workplace.

The odds represent the ratio between the probability of an event occurring and the probability of that event not occurring, which can be expressed in the following form:

$$\xi = \frac{\pi}{1-\pi}$$

The above relation refers to the population (the full set), whereas in empirical research the probability values of a random event are not directly available. Instead, the research is based on relative frequencies, i.e., estimated probabilities of the occurrence of a given random variable:

$$\check{s} = \frac{p}{1-p}$$

It is important to note that the probability of an outcome ranges from 0 to 1, while the odds range from 0 to +∞.

To adapt the survey results, the collected responses are transformed into binary variables, based on the assumption that all responses except "Strongly agree" indicate the possibility of "Rule violation" concerning the stated statement. The transformation into a binary variable is therefore performed in this manner.

After conducting the procedure to form the binary logistic regression model, we obtain the following results.

The dependent variables in the binary logistic regression models are listed below.

Table 1. Binary logistic regression coefficients obtained from empirical data analysis in IBM SPSS

Dependent variable / Indepedent variable	Xp1	Xp2	Xp3	Xp4	Xp5	Xp6	Xp7
Arrive on time and stay until the end	1,340	-1,688	-,218	,002	-,111	-,509	-,169
Working hours for work only	,076	1,657	1,165	1,427	1,733	1,308	,742
Use resources rationally	1,221	1,793	-,034	,017	-1,480	-,270	-,837
Treat colleagues humanely	-1,649	1,559	,318	-,139	-,287	-,021	-,643
Obey supervisors	1,086	2,409	,590	,992	1,585	,823	1,287
Work as if for oneself	-,481	-,897	-,267	1,695	1,822	2,154	1,609
Help others if necessary	1,209	-18,582	-,158	-19,485	-,530	-19,112	-18,914
Stay longer if required	-1,415	,820	,607	-,327	-,854	-,406	,214
Gender	-1,014	-,827	,168	-1,510	,305	-,549	,517
Constant	-1,502	-3,697	-1,087	-,542	-2,552	-1,674	-4,107

Table 2. Dependent variables in the binary logistic regression model

Variable	Meaning
Xp1	Seatbelt should be fastened
Xp2	Right of way should be respected
Xp3	Pedestrians at unmarked crossings should be allowed
Xp4	No overtaking on solid lines
Xp5	Speed limits should be observed
Xp6	Parking restrictions should be respected
Xp7	Mobile phones should not be used except as allowed

The coefficients in the binary logistic regression model indicate how each variable contributes to increasing the likelihood of the corresponding traffic "violation," with a positive sign indicating an increase and a negative sign a decrease in the probability of the analyzed traffic violation.

Regarding respondent gender, it is observed that for women, the likelihood of committing the following violations increases:

- Allowing pedestrians at unmarked crossings
- Parking violations
- Mobile phone use while driving

For other violations, the likelihood decreases. Additionally, a significantly higher coefficient value for Xp7 ("Help others if necessary") reduces the chances of committing traffic violations in four of seven variables, with a magnitude of almost 20, while other coefficients are below 3 in absolute value.

RESEARCH RESULTS

The analysis of the collected data clearly indicates significant gender differences in the perception and application of ethical norms, both in traffic and in the workplace. These differences are not only statistically significant but also have practical implications for human resource management and policy-making aimed at promoting responsible and safe behavior.

Women, to a significantly greater extent, demonstrated adherence to basic traffic rules, such as wearing seat belts, respecting speed limits, and avoiding the use of mobile phones while driving. They also showed more consistent attitudes regarding the importance of observing working hours, maintaining professional relationships with colleagues, and rational use of workplace resources.

In contrast, men more frequently displayed a flexible or pragmatic approach to certain ethical issues, reflected in a lower level of strict compliance with rules and regulations, particularly in traffic behavior.

The analysis revealed a significant relationship between gender and ethical attitudes, indicating that gender can influence the formation of ethical behavior. Furthermore, it was found that attitudes toward ethics in traffic are linked to workplace ethics, confirming that an individual's general ethical stance affects their behavior in different contexts.

Recognizing gender differences enables organizations and institutions to target educational and preventive activities more effectively. For example, traffic safety campaigns can be tailored to address risky behaviors more common among men, while workplace programs can be developed to promote equal responsibility and discipline, taking gender-specific characteristics into account.

Such an approach contributes to better organization of traffic and work processes, reducing potential risks, strengthening teamwork, and utilizing human resources more efficiently, ultimately resulting in higher productivity and increased safety.

Incorporating a gender perspective into the analysis of ethical behavior provides a deeper understanding of the factors influencing behavior in key social domains. This enables the creation of more precise and effective policies and measures that promote ethical responsibility among all participants in traffic and the workplace, reducing conflicts and insecurity, while contributing to stronger social cohesion and sustainable development.

CONCLUSION

The stochastic analysis of gender-differentiated ethical patterns indicates that gender differences in behavior are not only statistically observable but also deeply rooted in social norms, cultural patterns, and socialization processes. Ethical behavior, both in traffic and in the workplace, is shaped through a complex interplay between individual beliefs and societal expectations. Women, who on average demonstrate a higher degree of compliance with ethical norms, contribute to a safer, more stable, and more responsible social environment. This study confirms the necessity of considering gender-specific characteristics when planning measures to improve safety and efficiency in traffic and workplace settings. By integrating a gender perspective into policy development and educational programs, it is possible not only to optimize processes but also to foster a more inclusive, just, and responsible society. From a sociological standpoint, such an approach represents an important step toward dismantling stereotypes and enhancing social cohesion, which is a crucial condition for long-term social development.

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